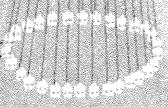


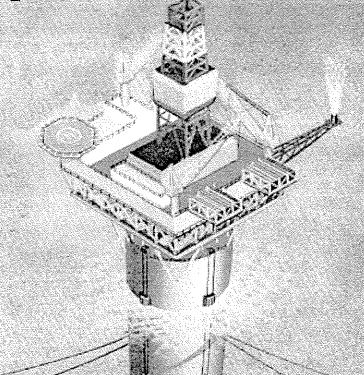
CEAC/MMS Seminar

New Orleans, LA

April 21, 1999



Composites Offshore



CEAC/MMS Seminar

New Orleans, LA

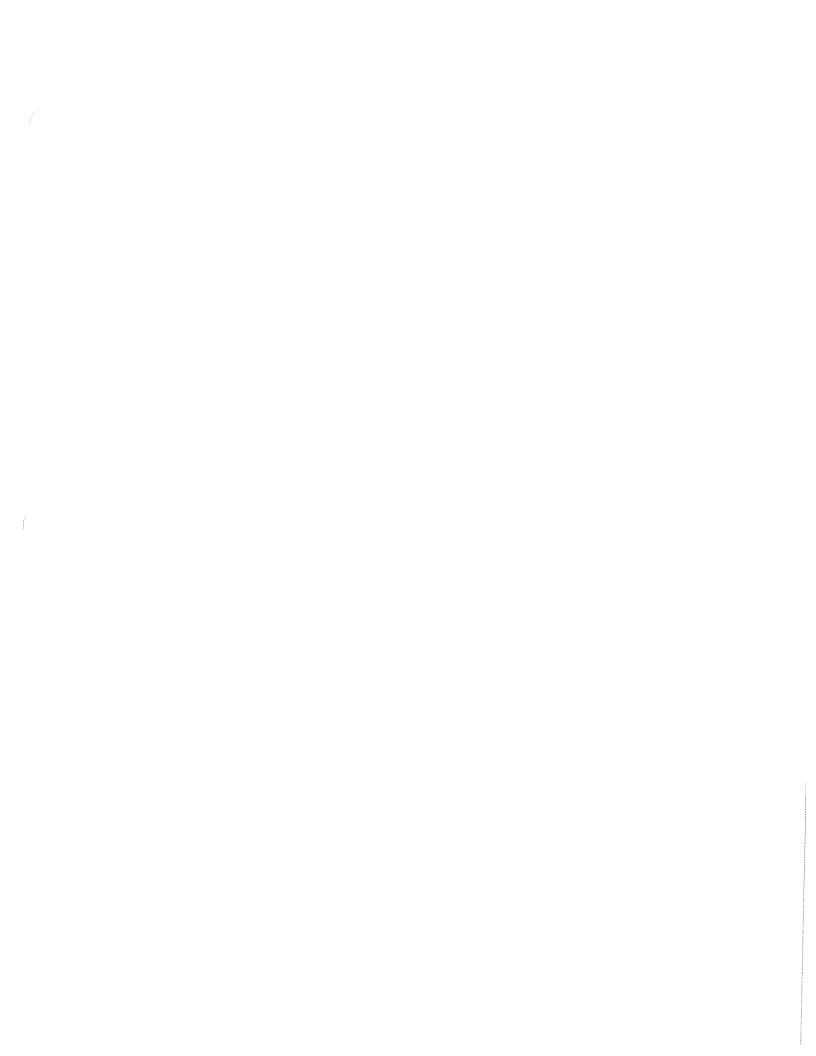
April 21, 1999

CEAC/MMS SEMINAR ON COMPOSITES OFFSHORE

April 21, 1999

MMS New Orleans Office 1201 Elmwood Park Boulevard First Floor Conference Room

9:00	Welcome Remarks	Charles Smith, MMS			
9:05	Seminar Program Structure	S. S. Wang, CEAC			
9:10	Composites Structures Offshore	Jerry Williams, CEAC			
9:40	Composite Experience On GOM TLP's	Mike Rainey, Shell			
10:10	Break				
10:30	FRP Pipe Standards & Specifications	Joie Folkers, Ameron			
11:00	Component Qualification	Him Lo, Shell			
11:30	Designing With Composites	Ozden Ochoa, OTRC			
12:00	Lunch				
1:00	Synthetic Fiber Moorings	Ray Ayers, Shell			
1:30	Composite Risers and Tendons	Mamdouh Salama, Conoco			
2:00	Risk and Reliability of Composite Components	Su Su Wang, CEAC			
2:30	Synergistic Advantages of Using Composites Systems Level Analysis	Richard Hill, Aker			
3:00	Break				
3:15	Panel Discussion - Regulatory Certification Issues Bill Cole, BP-Amoco, Moderator Jim Regg, MMS Perspective on Composites Lt. Chris Myskowski, U. S. Coast Guard Perspective on Composites Joe Fischer, Shell, Petroleum Industry Perspective on Composites Derek S. Novak, ABS, Certifying Agency Perspective on Composites				
4:30	Adjourn				











CEAC/MMS SEMINAR ON COMPOSITES OFFSHORE

SPEAKER ABSTRACTS

Composite Structures Offshore

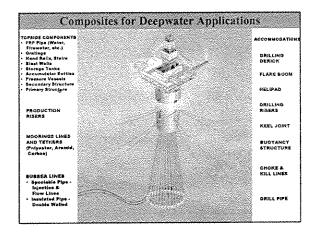
Jerry G. Williams Composites Engineering & Applications Center For Petroleum E&P University of Houston

Abstract

Major oil companies, composite product manufacturers, oil service companies, and regulatory agencies have worked together over the last ten years in a low-key, but concentrated effort to advance composites technology and make composites a viable option for oil industry applications. The technology has advanced significantly in recent years and lightly-loaded secondary structures such as low-pressure fiberglass pipe, gratings, and secondary structure are now routinely used in demanding offshore applications. Some applications in service, such as firewater ring mains and deluge pipe, are extremely safety critical and demanding tests and guidelines have been specified to insure their safe performance. Longer range, advanced composite applications are being developed to meet the demanding structural performance requirements imposed by deepwater developments including production and drilling risers, high-pressure spoolable pipe, pressure vessels, mooring ropes and tethers. An integral part of the successful introduction of high performance composites into offshore service is development of the supporting technology to insure safe and reliable performance and to define appropriate qualification tests, specifications and guidelines.

Corrosion resistance and weight control are the two primary factors motivating the interest and use of composite components offshore, however, several other assets characteristic of composites also provide benefits. Perhaps less recognized are some of the safety and environmental benefits composites provide. In a fire the low thermal conductivity of composites retards the rate of heat transfer, thus slowing the rise in temperature across walls or into conveyed fluids, and composite structures do not require toxic chemical corrosion inhibitors. Workers in both the construction phase and the operational phase typically prefer composites to metals for their human factors benefits including easier handling and reduced personal fatigue. advancements have been made in recent years in material formulations and fabrication processes and in the analytical methods used to design composites and predict their performance and reliability. Material suppliers and composite manufacturers have developed advanced resins which are improving performance and safety. For example, phenolic resin which in a fire exhibits low smoke and toxicity has traditionally been difficult to fabricate. Phenolic resin filament wound pipe and pultruded fiberglass grating products, however, have been successfully developed in recent years and are currently in service offshore. Structurally demanding applications such as a riser tensioner, highpressure accumulator bottle constructed of a hybrid combination of carbon and glass fibers and epoxy resin have also been recently introduced offshore. Hybrid construction combining difference materials to achieve the required structural performance while minimizing cost is another of the design flexibilities inherent in composites. The talk provides a background on composites with an overview of components currently used on offshore platforms and highlights proposed advanced applications under development. A few figures from the talk are presented on the following page.





Applications of Composites In Service

- Low Pressure Water Pipe.
- Gratings.
- · Handrails & Ladders.
- · Blast Walls.
- · Storage Tanks.
- High Pressure Vessels. (Riser Accumulator Bottles).
- Mooring Ropes.
- · Repair Using Carbon Fiber.

Offshore FRP Firewater Pipe Applications Development History Warin (Ring Main & Dry Deluge, GOM) Ursa (GOM), U.S. Coast Guard File Memo. Ram Powell (GOM) Mars (GOM), Neptune (Dry Deluge) Heidrun (GOK), Marinetech Research (UK) Auger (GOM). UKOOA Spec. Imortelle (Trinidad), Ewing Banks 205A(GOM) Valhall (Norway - Dry Deluge) AMAT Firewater Study (Norway) Southwest Fateh (Dubai - Dry Deluge) Marquette, CPP (GOM) SINTEF Studies (Multi-year, Norway) Limited Applications Before 1985



Potential New Composite Applications

- Platform Secondary Structure
- · Accommodation Modules, Walls
- Process Equipment
- Platform Primary Structure
- · High Pressure Pipe
- · Large Diameter Continuous Pipe
- Pressure Vessels
- Deepwater Moorings
- Low-Cost Carbon Fiber Tendons
- Drilling and Production Risers
- Drill Pipe and Torque Shafts
- Buoyancy Modules
- . Downhole Tools and Integrated Sensors



Standards & Certification

Standards, Specifications, Recommended Practice, and Qualification Test Methods

- API (15LR, 15HR)
- ASTM
- F1173 (Guideline for Use FRP On Ships)
- · Department of Defense

U.S. Coast Guard:

- FRP Pipe (PFM 1-98 16714)
- · Gratings (PFM 2-98 9078)

International:

- · OLF FRP Pipe Guideline (Norway)
- UKOOA FRP Pipe Specification → ISO

Composite Material Experience on Shell GOM TLP's

R.M. Rainey Staff Facilities Engineer Shell Deepwater Development

Abstract

This presentation will review the current application of composite materials on Shell Gulf of Mexico Tension Leg Platforms (TLP). Starting with the Mars TLP, Shell significantly increased the use of composites. Many of these were first time applications for Shell and the industry. The keys to successful conversion from standard solutions to composite materials will be discussed. In addition to reviewing current use, this presentation will also identify several future opportunities for composites on topside facilities.

Composite materials have been shown to offer several benefits to deepwater facilities. These include improved safety, total life cycle cost savings, reduced downtime, weight reduction, and reduced fabrication time.

Composite materials can improve safety in several ways. An example to be discussed is composite grating. It provides improved walking surfaces with better traction and less fatigue. During fabrication, composite grating can be installed earlier in the construction sequence to provide safer work surfaces for fabrication crews. The grating weighs approximately 1/3 of the weight of steel grating and therefore is easier and safer to install. This requires less people and equipment for installation. Due to its corrosion resistance, composite grating can be expected to last several times longer than steel grating. This can provide safe walking surfaces for decades with little or no maintenance. In case a repair is required, it can be made easier than steel and without hot work.

One of the primary drivers for the use of composite materials in deepwater applications is the significant weight reduction. In general, composites weigh 1/3 to 1/2 the weight of comparable steel components. This becomes significant when dealing with floating structures such as TLP's. Many studies have reported the total cost to support topsides payload to range from \$1 - 4 per pound. In many cases, the cost to float a component can be more than the cost of fabrication for the component. This provides a significant and permanent shift in deepwater economics towards composites and other light weight materials. This shift in economics along with the realization that composites positively influence other key variables such as safety, cycle time, and downtime is expected to increase their use on deepwater structures.

There are many opportunities for composites that can be envisioned in the next several years. The largest area is in structural components such as secondary deck beams, access platforms, hand rails, ladders, and, overboard casings and pull tubes. Piping also has several opportunities for expanded use in firewater systems, bilge and ballast, utility, produced water, and even low pressure process systems. Other opportunities include firewalls and fire protection systems as well as drilling equipment.

In summary, Shell has several very successful composite applications on numerous TLP's. Composites have proven to be cost effective as well as offering other significant benefits including safety. Composites have numerous opportunities on future topsides and this will be enhanced by the weight savings for floating deepwater structures.

Fiberglass Pipe Standards And Specifications

Joie L. Folkers – Engineering Manager Ameron International – Fiberglass Pipe Division, the Americas

Abstract

This presentation will review the most prominent regulatory agency specifications currently followed in the use and evaluation of fiberglass pipe in marine and offshore applications. In addition, specifications written by major oil companies will be reviewed. Comparisons and contrasts will be highlighted with the intent to promote the drafting and adoption of a universal, comprehensive specification.

A cursory summary will be given in a handout and a list of references provided.

Issues which need to be addressed on an industry-wide, global basis include pressure rating, fire endurance, fire reaction (flame spread and smoke generation) and electrical conductivity. The existing specifications have been written independently and are, consequently, not compatible.

A description of documents currently being drafted by ASTM and ISO committees will be given. The structure of a preferred specification, incorporating aspects of IMO and UKOOA documents will be proposed.

Significant input has been received from the U. S. Coast Guard, through an effort of a task force of the Composites Engineering and Applications Center (CEAC) from the University of Houston, in developing this approach.

Fiberglass pipe has outstanding thermal characteristics, making it a product to be considered for a broader range of services. A description of these characteristics and a challenge to recognizing their enhancement to safety and reliability will be given.

Designing With Composites

Ozden O. Ochoa Offshore Technology Research Center College Station, TX 77845

Abstract

Comprehensive mechanical and material behavior characterization is essential for robust design tools that reflect the actual service conditions for the composite structures. Fundamental issues of processing, manufacturing in relation to design and analysis will be presented from three different perspectives; service environment, testing rationale and computational simulations. Advantages associated with this approach include greater accessibility to design parameters, reduced computational demands, and the ability to customize and diversify. Furthermore, the methodology developed allows the designer to assess the impact of constituents on processing and global response.

The major issues addressed at laminate, lamina and constituent scales are; (i) the layup and fiber orientation to develop a robust and economical reinforcement architecture, (ii) response to combined loads, and (iii) hygrothermal effects, and (iv) residual stresses due to processing. Detailed structural response including hygrothermal loads are best-simulated finite element technique utilizing special user elements and user material models with progressive damage criteria. At the lamina and micro scales, as needed, the damage initiation and growth must be modeled with nonlinear material and geometry considerations. The material and mechanical characteristics for generating realistic design allowables may require non-standard tests in addition to conventional ones at multiple scales. Furthermore, the advanced computational tools that are necessary for capturing the anisotropic response need to be robust and simple.

Multidisciplinary and concurrent methodology has the potential of empowering the designer, the materials and manufacturing engineer by enabling the flow of continuous and interactive feedback throughout the development; from the initial to the final stages of testing and evaluation. Such an interaction demands a thorough understanding of anisotropic material behavior. The coupling of the design of these novel materials simultaneously with the structures that offer unique mechanical and physical properties lead to challenging optimization scenarios. Selected examples from automotive, aerospace and offshore applications will be used to illustrate the interdisciplinary and integrated approach of designing with composites.

Synthetic Fiber Moorings

Ray Ayers Shell E&P Technology Company

Abstract

In terms of performance and cost, polyester taut line mooring systems are being considered as superior to conventional mooring systems for mooring floating production units in the deeper waters of the Gulf of Mexico (GOM). In recent years, starting with the Fibre Tethers 2000 Joint Industry Program in 1995, the use of polyester fibers for mooring ropes has been recognized as the most cost effective synthetic fiber of those studied, and polyester should be the fiber of choice for mooring the first deepwater productionsystems in the GOM. Steel wire rope and chain mooring systems become less cost effective in water depths of perhaps 1500 meters and more.

At issue is that oil companies need assurance that the polyester moorings will be sufficiently robust, and will have sufficient durability for a life of 20 years or more, as required for a permanent mooring system. Of major concern is hurricane damage in the GOM. Petrobras is presently using polyester taut line mooring systems, but their regulatory and environmental conditions differ from those in the GOM.

In October of 1998 the DeepStar Joint Industry Program funded a research project (r1) to critically review all of the relevant work that has been done (principally in Europe) and determine what key issues remain for deploying polyester taut line mooring systems in the GOM. Shell E&P Technology Company is the contractor for this work, with subcontracted assistance from Stress Engineering Services. This paper contains a brief description of work in progress on that project.

Other DeepStar projects on synthetic moorings currently in progress, and reported separately at this conference, are: (a) "DeepStar Polyester Taut Leg Mooring System Test", which describes an evaluation of the recovered test mooring which was in place for several years near the Shell Auger TLP, and (b) "Development of API RP 2SM", which concerns development of a recommended practice on synthetic (not just polyester) mooring systems for the GOM.

This paper will present our current knowledge of the key issues which must be addressed in a mooring system design. Our scope is limited to permanently moored production systems, but many of the issues discussed are shared with those of temporary fiber rope mooring systems for mobile offshore drilling units (MODUs). In MODUs, rope handling is more of an issue because rope segments are reused from drilling site to drilling site, and the long-term fatigue life is a lesser issue.

RELIABILITY AND RISK ASSESSMENT OF OFFSHORE STRUCTURAL COMPOSITE COMPONENTS

Professor S. S. Wang

Composites Engineering and Applications Center (CEAC), and Department of Mechanical Engineering
University of Houston
4800 Calhoun Road
Houston, TX 77204-4792

Abstract

Advanced fiber composite materials are currently being considered for a wide range of primary load-bearing structural applications in offshore E & P systems, including both topside and subsea components. Advantages of utilizing light-weight, high-strength and high-stiffness composites have been known at the material level for sometime whereas the much more significant benefits at the system level has been just recognized. In order for offshore composite structures to be fully accepted in the E & P operations, reliability of the composite components must be well quantified and associated methodologies for a proper risk assessment need to be established. In this lecture, fundamental issues of composite material and structural failure will be discussed. The inherent uncertainties associated with deformations and failure in high-strength, brittle composites are addressed. The probabilistic composite material and structural mechanics used in developing reliability analysis for offshore composite structures will be presented. Discussion will also be made on the use of the API recommended LRFD methodology for composite platform structural design. The recent advances in reliability and risk assessment methodologies developed at CEAC for composite production risers in deepwater TLP applications will be discussed to illustrate the unique features in addressing the reliability issues for offshore composite structures.

Composite Risers and Tendons

Mamdouh M. Salama Conoco Inc., Ponca City, Oklahoma Tel: (580) 767-2738 <u>Mamdouh.m.salama@usa.conoco.com</u>

Abstract

Successful composite experiences in many topside offshore applications coupled with the need to reduce the life-cycle cost of deepwater development have motivated the industry to examine the application of composites in several critical applications, particularly for water depth sensitive components such as risers and tendons. Design and qualification of composite risers have been the subject of three recent joint industry studies. Composite production risers have been developed by a joint-industry project that was initiated in 1995 and is jointly funded by NIST/ATP. Also, low-pressure composite drilling risers have been developed by a joint-industry project that was initiated in 1995. High pressure composite risers are being developed as part of a joint industry project organized by Norske Conoco and Kvaerner and is partially funded by EU Thermie. Composite tendons has also been the subject of several studies, sponsored mainly by Conoco. In order to insure successful offshore application of these critical composite systems, several key technical issues that are unique to composite components must be addressed as part of the qualification program. These issues include performance requirements, damage mechanisms, damage protection strategy, allowable strength parameters, composite-metal interface joints, analysis methods, analysis validation, manufacturing quality control strategy, and testing. The presentation will address the basic elements that must be considered under each issue as part of the verification process to ensure and/or validate the following:

- 1. Accuracy and completeness of the performance requirements.
- 2. Identification of all possible failure modes.
- 3. Acceptability of the different elements in the design strategy to avoid these failure modes.
- 4. Basis for the analysis procedures and validating their accuracy.
- 5. Acceptability of the basis for selecting materials allowables and safety factors.
- 6. Validation of strength predictions of actual components.
- 7. Completeness of the quality assurance program.

The paper will discuss the riser system in more details and present the status of the current effort on carbon fiber tendons.

Synergistic Advantages of Using Composites in Deepwater Field Development

R.T. Hill Aker Maritime, ASA

Abstract

Composite materials offer many advantages for deepwater offshore platform applications because of their excellent corrosion and fatigue performance, high strength-to-weight ratio, and design flexibility. As the offshore industry moves aggressively to pursue deeper water field developments, composite materials are finding a wide range of new applications for both topside and subsea structures. While most of the current applications are secondary structures in the topside facilities, several major U.S. and international initiatives are underway to develop primary load-bearing system components.

Offshore market entry of composite components depend on combination of their potential to increase the platform performance, cost effectiveness, and technical risk compared to their steel counterparts. When favorable combination of these factors exists, technological, economical, and regulatory barriers can be overcome. Technical and commercial benefits of the composite components can be at the component level, such as a corrosion resistant firewater pipe or grating, or at the system integration level where savings in weight and performance of individual components cascade to provide synergistic cost and performance benefits in associated platform systems. An example of the latter could be a light-weight composite riser which would allow significant downsizing of the floating offshore platforms.

To facilitate the higher risk and resulting cost contingency associated with ultradeepwater reservoirs, the overall capital expenditure for surface production units will have to be reduced by 25-30%. This reduction be accomplished through system savings, only, and not made up through minor savings in components. Composite materials applications in riser, mooring, and tendon systems will enable such a reduction to be realized. Eventually this technology will allow further recovery of economically marginal shallow water reserves and make possible deepwater exploration and production.

This presentation will summarize potential impact of composite components on the deepwater field development and barriers in system integration.

Panel Discussion - Regulatory Issues

Bill Cole BP Amoco

Abstract

If major applications of composites are to occur in GOM deep water production facilities, the commitment must occur early in the life of the project to realize the benefits offered by light weight materials. Such commitments can be made only if regulatory approval is a near certainty. Substantial efforts are needed to develop the information, the data and the industry guidelines needed for regulatory bodies to approve the various components proposed as composites applications.

CEAC is prepared to lead efforts needed to prepare the industry to use composites technology. The efforts must involve all stake holders in this venture, the offshore operators, the supply side companies, and the regulators. CEC can address specific issues through workshops, task force activities, research projects and technology development projects funded by industry participants. CEAC has achieved impressive results in the past with each of these approaches. However, we need to improve our understanding of the regulatory responsibility and increase our efforts to address regulatory concerns as the applications of composites become more and more demanding.

The purpose of this panel discussions to clarify the issues form the regulatory point of view and to start the definition of a path forward. The path forward should address issues, but should be structures around the deliverable and schedule needed to meet the needs of the offshore industry.

Composites Offshore

Bill Cole

MMS Seminar April 21, 1999

Regulatory Issues

- Commitment to composites must come early in project life
- Requirements for commitment to composites will include
 - Regulatory policy allowing usage, or
 - well defined path for regulatory approval

CEAC Role

- · MMS is a charter member of CEAC
- CEAC members include regulators, supply side companies & offshore operators
- Mission facilitate use off composites in E&P
- CEAC can address specific issues through workshops, task force activities, research projects & industry technology development projects

Current Status

- USCG issued new policies for FRP pipe and grating in '98
- FRP tanks and vessels, a topic of conversation with USCG
- Synthetic Moorings
 - MMS/CEAC workshop in '98
 - Guideline document activities in progress
 - MMS/OTRC Project iniated in "99

Challenge For Panel

- · Help define path forward
 - Work process
 - Regulatory issues
 - Operator issues
 - Supply side issues
 - Schedule

Summary

• Future Actions/Timing

Components	Technology Maturity Level			
	Mature	Developing	Not Available	
FRP Pipe & Grating	Technology Regulatory Approval Commercial Products	System Integration Industry Guidelines User Awareness	None	
Synthetic Moorings	Technology, Commercial Products	User Awareness	System Integration Industry Guidelines Regulatory Approva	
Composite Spoolable Tubing	Technology	Commercial Products User Awareness	System Integration Industry Guidelines Regulatory Approva	
Composite Drill Riser	Technology	Commercial Products User Awareness	System Integration Industry Guidelines Regulatory Approva	
Composite Production Riser	Technology	Commercial Products User Awareness	System Integration Industry Guidelines Regulatory Approva	
FRP Tanks & Vessels	None	Technology Industry Guidelines	System Integration User Awareness Regulatory Approva	
Composite Deck Structure	None	Technology Commercial Products	System Integration User Awareness Regulatory Approva	
Carbon Fiber Tendons	None	Technology	System Integration User Awareness Regulatory Approva Commercial Product	

US Coast Guard Perspectives On Composites

Lt. Chris Myskowski United States Coast Guard

Abstract

The US Coast Guard has become very receptive when it comes to the acceptance of new and innovative designs and constructions of marine vessels and offshore structures. Application of advanced composite materials to areas where they have been historically prohibited is no exception. Fire safety concerns, however, remain as a formidable challenge that must be addressed if the acceptable applications for these materials are to continue to grow. Fire at sea has been the greatest fear of sailors throughout history. Despite a limitless water supply, fighting a fire at sea is fraught with difficulty-- reliance on power supplies that may be intimate with the fire, limited space to maneuver hoses and other fire-fighting equipment, rapidly spreading smoke and toxic fumes, and the ever present danger of being cut off from a safe escape route. It is easy to see why the acceptance of new proposals for the use of composites, largely composed of organic combustible materials, must be addressed with caution.

Traditionally, the Coast Guard applies a "steel or equivalent" standard to the construction of marine vessels and offshore structures. This has been interpreted as meaning a non-combustible material which by itself, or due to insulation has structural and integrity properties equivalent to steel. standard was developed in light of early twentieth century technology. Today, the development of advanced composite materials promising high performance, lower cost construction, and reduced maintenance, has demanded that new standards and regulations be developed that will allow the use of these materials while ensuring an adequate level of safety. The Coast Guard and the world community are ready and willing to accommodate new materials provided that a thorough and technically sound analysis is conducted to ensure the current level of safety will be maintained. Excerpts from the preamble to the High Speed Craft Code is evidence of this in stating that "the traditional method of regulating ships should not be accepted as being the only possible way of providing an appropriate level of safety, nor should it be assumed that another approach, using different criteria, could not be applied. Management of risk through accommodation, arrangement, active safety systems, restricted operations, quality management and human factors engineering should be considered in evaluating safety equivalent to current conventions."

Recognizing the fire safety challenges that the use of composite materials present, as well as the economic and technical need for these materials on both ships and offshore structures, the Coast Guard has been actively involved in R&D aimed at ensuring the safe application of these materials to marine

structures. One of the most significant R&D projects that the Coast Guard is working is with the DARPA MARITECH composite ship technologies consortium. This group is working to create full scale and bench scale fire tests and computational models to ensure structural integrity is maintained under fire exposures. Another example of R&D in composites is a Coast Guard partnership with CEAC, ASTM, ISO, and various testing laboratories that recently developed new policy for design, installation, and testing of composite piping and deck grating. The Coast Guard is also in collaboration with classification societies (RINA and DNV), and the Passenger Vessel Association to develop a process for analyzing novel designs for "equivalence" with prescribed designs.









CEAC/MMS SEMINAR ON COMPOSITES OFFSHORE

Background Papers

Standardards and Sportifications

Tiberglass Pipe Division Ameron International Hadineering Manager Joie L. Folkers Americas

Agency Specifications

- International Martine Organization
- Assembly Resolution A.753(18)
- Inited States Coast Guard
- N. V. I. C. 11-86, PFM 1-98
- DESCOLUCION OF STREET
- 1 1997 Rules for Steel Ships
- American Society of Testing and Materials Designation: F 1173-95
- United Kingdom Offshore Operators Assoc.

Royal Dutch / Shell Group DEP 31, 40, 10, 19-Gen.

Amoco Corporation

A PIPE-NW-FRP-1

Mobil Oil Company

I EPS 70-B-13

Issues Addressed

- Prossure Rating
- Tire Angelrance
- Tame Noted
- Smoke Generation and Toxicity
- Mectrical Conductivity
- | Quality Assurance

External Pressure

- Maial Strength
- Temperature Rating
- Impact Resistance
- Shock Loading
- Flow Velocity
- Transient Pressure
- Chemical Resistance

TERNOTER RATIO

ASTM ABS WOOA Short Short

うらい。

Burst/4 or 100,000 hr./2.5

4:1 Safety Factor

Same as IMO [Draft] Same as IMO

Pipe/Fitting Matrix Amended UKOOA

Simplified Matrix

1.5x Rating for 5 min.

Levels 1 & 2 - Dry

Level 3 - Wet

Jet Fire, Furnace, L3

Same as IMO

Same as IMO

Classification Code

Classification Code

Classification Code

Wet/Dry Jet Fire and Flame Test

じついつ

ASTIM

ABS

UKOOA

Short

BP Amoco

Mobil

FIFE ROUGHOL

Agency
INCO
USCCG
ASTIN
ABS
ASTIN
AB

Flame, Smoke, Tox.
Shoke, Flammability
Flame, Smoke, Tox.
Flame, Smoke, Tox.
Flame Spread
References Only
References Only

Methods References

Not Specified

TIBOUTION BOUNDERLY

A See Education of the second of the second

ASTIN ABS

UKOOA Shell BP Amoco Wobii

Socilication and the second se

Al Pipe in Hazardous

Areas

In Tanks, Fuel Lines As Required (w/Spec)

Same as IMO, Grounding Visible "Where Specified"

As Required
"Where Specified"
Grounded at Metal

CHIVERSH SPECIFICATION

- Develop a comprehensive classification Code: (UKOOA as a model)
- Develop an application/location matrix for offshore structures. (IMO as a
- Apply code to each cell of matrix,

Secondially Fibergless

- TOW THEMAL CONDUCTIVITY
- Meeps fluid in pipe "cool" when exposed to
- Low Heat Capacitance
- Fluid introduced to dry pipe (deluge system) remains iquici

KON TOSE COESIGOESEIOES

Pressure Rating

- Test Components vs. Rating, not Pipe
- Diminishing Safety Factors with Longer Term

- Heat Flux only Valid Property to Define Fire
- Qualify Size Tested and Larger, not Smaller

■ Mectrical Conductivity

- Conductive Fibers Increase Performance
- Conductive Fillers Reduce Performance

Emerging and Potential Composite Applications for Deepwater Offshore Operations

F. Joseph Fischer¹ and Mamdouh M. Salama²

REFERENCE: F. J. Fischer and M. M. Salama, "Emerging and Potential Composite Applications for Deepwater Offshore Operations," *Composite Materials for Offshore Operations* – 2, S. S. Wang, J. G. Williams, and K. H. Lo, Eds., American Bureau of Shipping, 1999, pp. 37-55.

ABSTRACT

The petroleum industry has long recognized the potential for composite-material products in its offshore operations. Particularly attractive are composites' high strength-to-weight ratios and their resistance to corrosion. Recent estimates by the industry indicate that topsides', piping, riser, tendon and other composite needs over the next ten (10) years could reach nearly 100,000 tons having a market value of around \$3B (at \$15/lb). The last several years have witnessed phenomenal growth of development activities for high-performance products such as coiled tubing and marine production risers due, in part, to reduced material costs associated with the decline of defense and aerospace demands, and federal-government "encouragement" such as the NIST/ATP program that provides "matching funds" for high-risk projects focused on bringing commercially viable products for the offshore to the marketplace. The status of these activities are reviewed.

INTRODUCTION

As part of the oil industry's efforts to reduce the life-cycle costs of deepwater developments and to improve reliability, considerable attention is being devoted to the evaluation and application of innovative and cost-competitive alternative materials. Composites offer many potential advantages for marine construction based on their low density, corrosion resistance, and excellent fatigue performance. In addition, the use of composites permits greater design flexibility for tailoring properties to meet specific design requirements, thus promoting better system-oriented, cost-effective solutions. Also, new innovations are being developed to embed fiber optics and electrical conductors into the composite part to monitor quality during manufacturing, structural

¹ Shell E&P Technology Company

² Conoco Inc.

integrity and loads during service, and to obtain operational conditions from remote locations.

In this paper, the definition of composite materials is limited to fiber-reinforced polymer (FRP) materials. FRP materials consist of small-diameter fibers of high strength and modulus embedded in a matrix with bonded interfaces which permits the fibers and matrix to form a new material which captures the desirable characteristics of each. The most common fibers are glass, carbon and aramid. Polymeric matrix materials can be thermoset or thermoplastic. The most common polymeric matrix materials are polyester, vinyl ester, phenolic, acrylics and epoxy. Fibers are usually incorporated into the matrix in long continuous lengths but are sometimes utilized as short discontinuous fibers.

Although the traditional engineering material for offshore structures is steel, synthetic materials and advanced composites have been receiving much attention by the oil industry as demonstrated by the many joint industry projects, special meetings, and workshops [1-3]. Although on a one-on-one basis, components made of these materials will most likely be more expensive than identical, or functionally equivalent, steel counterparts, on a performance-equated basis, the economic advantage of composite components can often be demonstrated by examining their impact in reducing system and full-cycle costs.

The primary purpose of a floating offshore platform, e.g., a TLP, is to support the topside "payload" which includes the weight of the accommodation's module, helideck, production and process facilities and drilling equipment. In addition, the hull must support the deck structure and the tension loads associated with the production and drilling risers and any mooring system. A reduction in topside weight will reduce the size, weight and cost of the supporting structure (deck and hull) with the savings' premium dependent on the type and size of the structure and design parameters including environmental loads [4]. There is a significant economic incentive to reduce the topside weight through the use of composites. The ranges of payload premiums, that are being considered by the industry as bases for assessing the cost-effectiveness of weight-reduction options, are \$4-7/lb of payload for TLPs, \$3-5/lb for semisubmersibles, \$1-3/lb for ships, and \$1-2/lb for Spars [5].

This paper reviews current and emerging applications of composites and identifies potential opportunities associated with deepwater oil-industry developments. The paper also presents a discussion of financial incentives to develop composite applications, identifies the main challenges facing the introduction of composites into service and discusses steps currently being taken to address these issues.

CURRENT MARINE AND OFFSHORE APPLICATIONS

Glass fibers were commercially introduced in 1938 and were used initially for insulation and acoustic isolation applications. One of the first structural applications for composites

was in the automotive industry where fiberglass was introduced in the 1950's for sports car bodies. Fiberglass pipes and tanks have been used in the onshore oil industry for almost 45 years [6]. Advanced composites were developed initially for military and aircraft applications where high stiffness and strength properties have a significant impact on performance. Interest in the use of composites to improve performance in offshore oil industry applications began in the early 1980's driven primarily by interest in eliminating corrosion and reducing weight on offshore platforms. For most oil-industry applications, the high cost of composites characteristic of the aerospace industry is prohibitive.

Fiberglass composites, and to a lesser extent carbon, Kevlar®, and Nomex® composites, have been used by the offshore oil industry in a variety of applications. These include storage tanks, pressure vessels, low pressure pipes, reinforcements for flexible pipes, torque shafts, structural parts, seals, gratings, fire and blast walls, cable trays, etc. The motives are lower weight, less maintenance, and reduced installation costs. Some specific examples for the offshore application of fiberglass composites include fire water piping (Amoco's Valhall, Conoco's Marquette, Shell's Mars), seawater piping (Dubai, Conoco's Heidrun, Phillips Ekofisk), storage vessels (Conoco's Heidrun, Amoco's Davy/Bessemer), grating (Shell's Mars and Ram-Powell), mud mats (Elf's Garibaldi C), and subsea wellhead protection (Shell's Vigidis and Draugen).

It should be noted that only during the last decade has the fiberglass industry started to seriously consider new technologies such as improved resins, reliable connections, selectively using carbon fibers, implementing better quality control and NDT techniques, publishing better design and installation guidelines, and using improved fire resistance formulations and coatings. Therefore, past negative experiences with fiberglass composites should not be used as a basis for judging current materials. As an example, in the past many operators have had very disappointing experiences with leaks of fiberglass pipe joints, but recent applications of GRP pipes on platforms such as Heidrun and Ram-Powell have shown that the leak rate for several thousands of field joints was less than 0.1%.

Composites have also been used for many high-pressure vessel applications. Compressed natural gas pressure vessels from glass and carbon fiber composites with a high-density polyethylene liner have been in use for many years. Composite pressure vessels have been developed and qualified for use as mud gas separators (MGS) as part of a JIP in Norway. The primary advantages that composite MGS offer are reduced maintenance due to composite's corrosion resistance, and 50% weight savings over carbon steel vessel.

Composite accumulator vessels [7] have been used for production-riser tensioning systems on both the Mars and Ram-Powell TLPs. These vessels, shown in Figure 1, have a volume of 11,500 in³ (17.3 inch OD, 82.5 inch length, 365 lb weight) and are ASME code section X, PR certified for 35 year service life at 3000 psi operating pressure (burst pressure > 15,000 psi). They are constructed of carbon/S-glass fiber epoxy composite over an HDPE liner with 316L stainless steel bosses. While the weight of these composite vessels was about 1/3 the weight of the equivalent steel vessels, the cost of the

composite vessels was actually lower than the steel vessels. The estimated cost for the composite vessels is \$4,500 per vessel. This cost can be greatly reduced if the ASME code, which sets the safety factor based on the poor strength-time dependence of E-glass composites, is changed to account for the better strength-time dependence of carbon fiber composites. For carbon fiber composites, a safety factor of 2 to 3 is more realistic than the currently specified factor of 5.

EMERGING AND POTENTIAL COMPOSITE APPLICATIONS

Successful composite experiences coupled with the need to reduce the life-cycle costs of deepwater developments has motivated the offshore industry to examine the application of composites in several critical applications. However, wide-spread applications of advanced composites in the oil industry will occur only if composite products become affordable using low cost manufacturing processes and low cost fibers. Much of the cost of aerospace components is introduced by the pedigree record required to ensure high performance and reliability. The trade-off to reduce cost for oil-industry applications is to increase the safety factors to account for material variability and to accept lower material design allowables which translates, unfortunately, into lower weight savings. This compromise, however, is normally acceptable since the weight comparison for the oil industry is relative to steel rather than aluminum, the material of choice for most aerospace applications. Weight savings of 50 percent or more are possible when composites replace steel components. Weight savings for aerospace applications based on replacing aluminum commonly range from 25 to 30 percent.

So far, the main emphasis on potential applications of advanced composites for the offshore industry has focused on high-pressure tubulars (above 1000 psi pressure) which are either discrete length (20 to 80 feet) for use as drilling and production risers, choke and kill lines, tubing, casing, and pipe, or continuous (many thousands of feet long) for use as coiled tubing [8] and flowlines [9]. Continuous pipes have relatively small diameters (<6 inch) and are designed to be spooled. Spoolable composite pipes have been proposed for use as coiled tubing, velocity strings, capillary tubes, subsea pipeline clean out lines, subsea flow lines and subsea control lines. High-pressure composite coiled tubing is attracting major attention because it provides enabling capabilities to work over, log and complete highly deviated wells as well as provide operational improvements for a wide variety of other oil field applications.

There also are other applications under consideration for composites which do not fall under the high-pressure tubular classification such as TLP tendons. One proposed tendon concept uses a strand assembled of many continuous small diameter carbon fiber rods or a belt laminate constructed using carbon fiber rods. The tether, like coiled tubing, would be designed to be spoolable to improve the economics of installation.

Production Risers

Composite production risers have been the subject of many studies because they reduce the required pretension and simplify the riser tensioners. With the introduction of composite risers, tensioner stroke and riser stretch may remain unchanged, but the stroke-related load on the tensioner (and the supporting deck structure) will be nearly halved, resulting in a reduction of the operational payload and simplification of the tensioner structure [10].

During 1985 to 1989, several major oil companies joined with the Institut FranHais du P9trole and Aerospatiale to develop and evaluate a 9-inch composite production riser. The riser tubular was fabricated from a hybrid of carbon and S-glass fiber/epoxy composites. The pipe was designed to withstand a combined internal pressure of 15,000 psi and axial tension of 450 tonne. The pipe was also designed to withstand a collapse pressure of 5400 psi. The study included several static, fatigue, multi-axial loading and damage-assessment tests. As a follow-up to this study, Brunswick Composites (currently Lincoln Composites), Coflexip, IFP, and Aerospatiale engaged in a project to reduce the cost of the risers by optimizing the manufacturing process and the design. The design optimization included simplifying the composite-to-metal interface and using lower-cost E-glass instead of S-glass.

The drop in the price of advanced composites in recent years and the current accelerated activities in deepwater exploration and production have prompted renewed interest in using composites for production risers. A joint-industry project focusing on composite production risers, jointly funded by the National Institute of Standards and Technology (NIST) Advanced Technology Program (ATP), is currently underway [11, 12]. The goals of the project are to design, develop, manufacture, test and qualify a commercially viable production riser made with fiber-reinforced polymeric composites. Lincoln Composites is leading the effort in engineering design and fabrication of the composite riser. A concentrated effort was conducted in the first part of the project to design a low-cost, light-weight composite production riser suitable for deepwater (3000-5000 feet). The functional requirements and performance specifications of the riser were determined by oil-company participants and were based on the results of an iterative analysis of the response of the composite production riser to representative platform motions and direct environmental loads.

The composite production riser is a hybrid structure design with carbon and glass fibers embedded in an epoxy matrix. The composite-to-metal interface design relies on a special configuration which has been used before in some aerospace structures. A premium light-weight threaded connection is used for the metal connector. The external geometry of the metal connector has been chosen to accommodate standard riser handling equipment. Hence, no special equipment will be required to handle and install the composite production riser. Internal and external liners will be incorporated into the production riser to provide fluid-tight pressure barriers and protection from damage due

to accidental impact and wear. Full-scale and subscale riser spool pieces are being fabricated and will be tested to validate the design assumptions and riser performance characteristics. Qualification of the composite production-riser joint for field service has been planned and will be carried out upon completion of fabrication of the full-scale (diameter) riser joints as shown in Figure 2. Other elements of the project include a detailed reliability and safety study to ensure serviceability of the composite production riser, and development of advanced design/analysis methods to enable direct translation of the results of this project to other production-riser designs.

In addition to the production riser pipe, composites are being considered for other riser components such as tapered stress joints and tensioners. Currently, tapered joints are conceptually designed using a hybrid of a steel or titanium riser pipe, with a tapered outer wrap of fiberglass and carbon fiber/epoxy composite.

Drilling Risers

Initial efforts in applying composites to drilling risers focused on the use of composite choke and kill lines. A study conducted by IFP on an 18 3/4" OD steel riser having 3 ½" kill and choke lines showed that these two small-diameter lines represented 30% of the total mass of the riser. Replacing them with composite lines reduced the total mass by 24%. The reduction in mass was important in reducing the dynamic forces on the riser by reducing the inertia forces and decreasing the longitudinal resonant period of the hung riser which reduces the dynamic amplification of the heave-induced axial forces. In addition, the mass reduction due to application of composite choke and kill lines reduced the quantity of costly syntactic foam, reduced current-induced drag forces, and provided a 600 tonne reduction in deck load when the riser is stacked on the vessel. To prove the suitability of composite choke and kill lines, a field trial in deepwater was carried out in 1983. Three 15 m long composite tubes were run on the marine riser of the Pentagone 84 during three drilling campaigns in the North Sea. Operational behavior of the tubes was fully satisfactory, and a burst test performed on one sample after the field trial showed no deterioration of performance. The composite tubes were manufactured using carbon and glass fibers and had the following characteristics: ID = 4 inch, Length = 47 ft, Weight in water = 321 lb, Burst Pressure = 170 MPa (24,000 psi). Several companies have the capability to design and produce 15,000 psi choke and kill line. The estimated cost for 50 ft, 3 inch ID joints with metal couplings is \$15,000 per joint. The weight in air of the 50 ft joint is 700 lb, including couplings.

As a follow-up to the IFP work, Northrop Grumman Marine Systems (formerly Westinghouse Marine) is leading a joint-industry research and development venture to develop technology to commercialize light-weight advanced composite tubulars for deepwater oil and gas exploration and production [13]. The venture is also funded jointly by NIST/ATP. The first target application of the technology is a composite low-pressure drilling riser system with the riser body (20-inch diameter) and high-pressure (15,000 psi) choke and kill lines made of advanced composites. The venture is currently more than half way through a 3-year, \$4.8 million project. The objective of the project is to

demonstrate successful deployment of a light-weight advanced composite drilling riser pup joint prototype in a deepwater drilling program. The project plan includes material characterization, design, fabrication and land test of riser prototypes in addition to fabrication and testing of an in-the-water prototype. Preliminary design and fabrication of two 25-ft long drilling-riser main-body prototypes (Figure 3) as well as high-pressure choke and kill line prototypes have been completed. The air weight of the composite system is less than 50 % of the steel system. Estimated total costs of steel and composite systems for 6000 ft water depth (consists of: 79 riser joints (75 ft each), 1 telescopic joint, 4 pup joints (5 -30 ft), 1 tensioning ring, and syntactic foam) are \$11.7 million and \$20.7 million, respectively.

In addition to this low-pressure drilling riser work, a JIP led by Norske Conoco and Statoil is underway to design, qualify, and field test a 22 inch high pressure composite drilling riser for TLP applications. Upon the successful development, a full size riser joint is planned for testing on the Heidrun TLP with the currently used titanium riser. The joint is designed with a carbon-epoxy composite body, titanium internal liner, elastomeric external liner, and titanium flanges.

TLP Tendons

TLP tendons are stiffness-critical structural elements that ensure that the platform heave, roll, and pitch natural periods are limited to 4 seconds to avoid resonance (which is known to increase fatigue damage and extreme loads). While steel has been used to-date, carbon fiber (PAN or pitch) composites in a long-laid parallel-wire construction and large diameter strands are being considered. Strands of up to 5 1/8 inch (131 mm) diameter and 3.8 million pounds breaking strength have been produced for suspension bridges. Larger size strands of about 10 inches (254 mm) may be required for TLP applications. The strands are formed using a track based manufacturing system from 3 to 5 mm wire-rods that are supplied in the form of 6 ft diameter coils. The helical bundle with a lay-to-diameter ratio of 75-to-1 is formed together without inducing any torsional stresses into the rods. Intermittent tape wrappings can be applied to assure strand integrity during coiling and handling. To protect the strand and improve handling, a thermoplastic jacket can be fitted to the strand. Fatigue tests were conducted on 500,000 pounds breaking strength carbon-vinyl ester composite strands with potted terminations and showed that the fatigue life is ten times longer than steel strands [14].

In order to achieve a 4 second design criterion for a Heidrun type concrete TLP in 4400 feet in the North Sea, the required tendon stiffness per corner will be about 300 MN/m. If the tendons are made of steel, the mass of the tendons will exceed 80,000 mT and the tendon pipe design will be very complicated to achieve a reasonable weight in water and number of tendons. If the tendon system is fabricated of high modulus (55 x 10⁶ psi) carbon fiber composites, the mass will be about 14,000 mT), and under these conditions the maximum stresses in the tendon will be about 20% of its ultimate strength. This type of TLP application may not be practical for deepwater because of the platform size and the difficulty in securing this large amount of carbon fibers at a reasonable price. Note

that the current worldwide production capacity for PAN-based carbon fiber is limited to about 25 million pounds per year. Since carbon fiber composite tendons possess superior fatigue resistance, the possibility and effects of relaxing the heave natural period limitation should be considered which, if found to be feasible, would mean a significant reduction in the required amount of carbon fiber and, thus, increase its competitiveness with steel.

Although the cost of the currently available high-stiffness composite material is high, Conoco's current efforts to develop low cost discontinuous high-stiffness (50 to 75 msi) pitch carbon fiber and the recent introduction of a low cost (\$6-8/lb) intermediate stiffness (30 to 35 msi) carbon fiber by Zoltek change the economic picture. An economic comparison between steel tendons and composite tendons using the discontinuous carbon fiber showed a cost savings between \$30 to 300 MM, depending on the TLP size and waterdepth, in favor of composites. This economic advantage has motivated several studies to develop and qualify carbon fiber composite tendons.

Non-Bonded (Flexible) Spoolable Pipe

Non-bonded flexible risers are critical elements in floating systems for deepwater offshore oil and gas production [15]. Current applications in increasingly demanding environments, with a design temperature up to 265° F, a design pressure in excess of 5000 psi, sour production fluids, waterdepth exceeding 1000 meters, severe wave and current conditions, and larger diameters (more than 10-inch inside diameter), are challenging conventional flexible pipe design and construction. A non-bonded flexible pipe is designed as a multi-layer conduit consisting of thermoplastic layers for sealing the conveyed fluid from the external environment and metallic layers of carbon steel to provide axial and hoop structural reinforcements. In deeper water where longer-length flexible pipes will be used, the weight of the carbon steel reinforcements becomes a critical factor in the design of a flexible pipe. The large tension load induced by the pipe weight could lead to unacceptable stress levels in the pipe structure and excessively large deck and installation loads. As the pipe stress level increases, larger cross-sectional areas of the steel members are required, further increasing the weight of the pipe. To reduce the pipe unit weight, while retaining the required strength level, polymeric composites have been proposed and used as armor wires to replace the steel axial reinforcement.

The first application of composites in a non-bonded flexible pipe was carried out by Coflexip Stena Offshore using armor wires made of glass-fiber reinforced epoxy (Figure 4). The shapes of the composite wires are flat and rectangular similar to those used for steel armor wires. To minimize residual stresses after laying, the composite wires are initially preformed to a given lay diameter and armoring angle. Coflexip Stena Offshore has manufactured and installed flexible risers with glass-fiber composite armors for Petrobras in Brazil.

Wellstream is leading a project to investigate the use of fiber-reinforced thermoplastic composite strips/wires to replace the carbon steel tension armor layers in non-bonded flexible pipe for deepwater sour service [15]. This material substitution reduces the submerged weight of the flexible pipe by about 30%. Work is underway to evaluate the performance of the composite armor flexible pipe; to develop sensors for life monitoring of the thermoplastic composite armor; and to develop a service life model of the armor. The cost of the composite-armor flexible pipe is expected to be higher than that of a steel-armor pipe but the total system cost-savings associated with the lighter weight flexible pipe are expected to be sufficient to offset the higher cost of the composite flexible pipe.

Bonded Spoolable Pipes

Light-weight, spoolable, all-composite tubulars are beginning to attract attention as alternatives to the heavier non-bonded steel and steel-composite flexible pipe. With recent advancements in manufacturing processes, spoolable composite tubulars can now be produced in long continuous lengths. A typical spoolable composite tubular usually consists of load-bearing layers of carbon, glass, and/or kevlar fibers in a polymeric matrix. The fluid-pressure barrier is provided by means of a chemically resistant thermoset or thermoplastic inner liner. If needed, an outer thermoplastic protective layer can be added to the composite structural layers. Interest in the use of composite spoolable tubulars can be seen from the various current development efforts described below.

COMPIPE has recently completed the first phase of a composite flowline joint-industry project [16]. The objectives of the project are to develop and qualify a spoolable composite flowline. The diameter of the flowline studied in the project was in the 100 mm to 250 mm range and the pressure rating was in the 100 bar to 350 bar range. Cost comparisons of composite flowline with coated carbon steel, conventional flexible flowline, duplex steel, and 13% Cr steel flowline show that a continuous polymeric composite flowline is economically viable. The total cost-savings in pipe material and fabrication range from 17% to 48% when compared with a duplex steel flowline. The cost of installing a composite flowline is similar to that of a reeled steel line.

Fiberspar has developed manufacturing technology for long continuous spoolable composite tubulars and is proposing a joint-industry project to qualify non-metallic bonded spoolable tubulars for offshore applications. Fiberspar estimates that the cost of a spoolable composite tubular will be competitive with the acquisition cost of a similar API 17J flexible pipe on a per-foot basis. However, the life cycle cost is expected to be reduced because the spoolable composite tubular is corrosion resistant, lighter and easier to deploy, has longer fatigue life, and has the potential to reduce overall riser system complexities and costs. Figure 5 shows a 4-inch flowline having a 3-inch ID designed and built by Fiberspar. It is designed for 3,000-psi operating pressure. The connector is a a 4-inch FMC WECO (hammer blow union) designed for Arctic conditions.

A similar joint-industry project is currently underway, led by Hydril and jointly funded by NIST/ATP, to develop an advanced manufacturing method for long continuous spoolable composite tubulars in the 1-inch to 6-inch diameter range for deepwater applications in the Gulf of Mexico. The current project is based on the results of an earlier joint-industry project on composite coiled tubing which demonstrated that superior performance can be realized with a properly designed and fabricated spoolable composite tubular.

The above discussion on spoolable composite tubulars concentrated mainly on pipes made with thermoset resins. It should be pointed out here that a new class of spoolable composite tubulars made with fiber-reinforced thermoplastics [17] is beginning to emerge in the oil and gas industry. For the manufacture of this reinforced thermoplastic pipe, pre-formed fiber-reinforced tapes having a compatible thermoplastic matrix are utilized. Initially, layers of these tapes are helically wound around a thermoplastic tubular. Preferably, tape widths are such that for a given pipe outer diameter and a given windangle, the pipe outer surface is completely covered by each tape layer. Usually, pairs of tape layers are applied having opposite wind-angles for each layer to ensure torque balance of the fabricated pipe. Following application of one or more pairs of tape layers, an outer layer of thermoplastic pipe is co-extruded on top of the tape-wrapped inner pipe.

The several layers of this sandwich-type construction are usually bonded together by thermal or other means either as the tape layering/reinforcement proceeds or following the co-extrusion step. Wavin of the Netherlands has demonstrated the continuous manufacture of such pipe by producing 200 feet of 4-inch pipe having two tape layers. Tubes d'Aquitaine of France [17] are currently manufacturing both the reinforced tapes necessary for this manufacture as-well-as finite-length pipes having various diameters and tape layers (pressure ratings). Tubes d'Aquitaine have also designed and qualified a cost-effective, easy-to-install threaded metal connector. Their ultimate goal, that is currently being realized for 3-inch pipe, is continuous fabrication. A reel of pipe having intermediate connectors every 12 m is shown in Figure 6. (Photo courtesy of Tubes d'Aquitaine). The potential of this class of spoolable tubulars for riser applications should be investigated.

Substructure

Both sandwich and pultruded composites are being considered substitutes for steel flooring which is currently fabricated from plates welded on I or U shaped beams, and then laid on the primary beams of the deck. Coflexip developed composite flooring that is made by juxtaposition of composite beams and is stiff enough to be laid directly on the primary deck beams. The low cost pultrusion process is used to produce these beams that are formed with profiles to allow interlocking and equipment installation. Composite beams can be built with higher strength and more fire resistance than steel, which could have special applications in rig floors and hull support [18].

The application of composites for load bearing floors, bulkheads, helidecks and living quarters can take advantage of the current development efforts of composite bridges. Researchers at Lawrence Technological University (Southfield, MI) are studying the use of glass and carbon fibers for an experimental road bridge. At the University of California (San Diego), researchers are using carbon laminates to develop space-truss structures that strengthen highway bridge columns, and researchers at the University of Arizona (Tucson) are studying ways to use carbon laminates to strengthen masonry walls and concrete columns. Aramid, glass, and carbon fiber composite materials, developed by NEFCOM Corp. in Japan, are already used in a grid reinforcement system for concrete structures.

Composites for Deepwater Drilling

Recognizing the potential of composite materials to provide additional weight savings to the RamRig, a study was conducted to assess the application of composites on several critical components. These components were selected because of ease of implementation by being in use or already qualified and based on weight advantage as identified by the rig designer. Table 1 summarizes the results of this study giving budgetary weight savings and cost premiums for composites over conventional materials and highlighting components which can be readily replaced using off-the-shelf composite-materials technology of the day.

Composites for Subsea Development

As subsea developments move to deeper waters, the use of ROVs will expand for installation, retrieval and repair functions. The effective use of ROVs requires the development of light-weight equipment and tools. Components for which composites can offer major advantages include: manifold support foundation, mud mats, subsea protection cover, ROV manipulator, ROV skid, tools, control pod housing, vessels, accumulators, manifolds, and guide cones. Composites can also be used for components whose weight is water depth dependent, such as risers and umbilicals.

BARRIERS TO THE APPLICATION OF ADVANCED COMPOSITES

The expanded application of composites in the oil industry continues to face technical, financial and emotional barriers that must be overcome to allow the full potential of composites to be realized in critical offshore applications. Solutions to these barriers involve developing a more comprehensive design and manufacturing data base to allow competent risk assessment, establishment of reliable cost structure for both components and systems, and educating offshore contractors and suppliers to provide them with sufficient confidence to design and use these new materials.

Since the cost to meet these objectives is quite high, there is a need for alliances and consortia because resources are limited and no one company has the necessary skills to

succeed. This issue is currently being resolved by the joint sponsorship of these programs by government and industry such as the NIST/ATP which is currently being tapped by industry. Table 2 provides a summary of these NIST/ATP projects that are directed toward the oil and gas industry. In addition to these U.S. based programs, there are other programs being conducted in Norway. Two of these programs involve the development of a high-pressure composite drilling riser joint for field testing on the Heidrun TLP, and evaluation of composites for rig conversion.

The successful commercialization of advanced composite components requires that development programs incorporate input from all participants in the development including material supplier, manufacturer, engineering contractor, user, and regulatory agency. Advanced composite applications can often draw on the knowledge and extensive data base developed by defense and aerospace companies. Any successful development must include extensive economic analysis to ensure that the results are aligned with the needs of the oil industry, particularly deepwater development. Therefore, it must not be overlooked that the key to the successful development of composite components for the offshore oil industry is project implementation within a value chain partnership including owner, designer, material supplier, fabricator, regulator, and system integrator.

CONCLUSIONS AND RECOMMENDATIONS

- 1. Selected applications of advanced composites offer potential performance and economic advantages compared to steel. The introduction of primary structure products into service, however, will be slow in developing or even denied unless the manufacturer is provided support in defining the requirements and evaluating the performance of new products including making facilities available for field testing.
- 2. The key to the successful development of composite components for the offshore oil industry is project implementation within a value chain partnership including owner, designer, material supplier, fabricator, regulator, and system integrator.
- 3. Regulatory agencies have demonstrated receptiveness to new technology and no regulatory requirements are foreseen that will prohibit the use of composites for offshore applications. Composites must, similar to other materials, be "fit for purpose" which includes satisfying economic metrics and complying with safety and environmental requirements.
- 4. While cost differentials between steel and composites for individual components vary, on average a composite component costs twice that of an equivalent steel component, and weighs half as much. This cost premium may be offset by the reduced payload, maintenance, and handling requirements. For some components,

- such as high pressure vessels, composites can be lighter and lower in cost than steel vessels.
- 5. The cost of composites can be significantly reduced if design codes for pressure vessels change to differentiate between safety factors for fiberglass and carbon fiber composites, and for composites with and without liners.

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Table 1. Summary of Weight Savings and Cost Premiums for Composites

Component	Stee	I	Composites	
	Wt (lb)	Cost (\$)	Wt (lb)	Cost (\$)
Two 3" C&K lines 10,000 psi operating Pres.	386,400	1,472,000	128,800	2,760,000
Mud Separator I atm. oper. Press. 10.3 Barg Design Pres. 1.6 m ID, 4.6 m Height	7,700	70,000	5,500	88,500
30 Air Pressure vessels 3000 psi operating Press. 60,500 in ³ volume	360,000	900,000	37,500	720,000
Mud Pit 500 bbls capacity	2,400	9,000	800	10,000
Cladding 100 kt wind	50,000	350,000	23,000	300,000

Table 2. Summary of NIST/ATP Composite Projects

Program	Goal	Industry Sponsors	Cost (MM\$)
Production Riser	Design, manufacture and qualify 10 3/4", 6000 psi production riser	Lincoln Composites, Hexcel, Amoco, Shell, Conoco, Stress Engineering, Brown and Root, Hydril, CEAC	7.168
Drilling Riser	Design, manufacture and qualify 18", 3000 psi drilling riser	Nothrop Grumman, Hexcel, Deepstar, Vetco, Reading & Bates, OTRC	4.814
Drill Pipe	Design, manufacture and qualify drill pipe	Spyrotech, Phillips, Amoco, CEAC	2.77
Spoolable Pipe	Design, manufacture and qualify spoolable pipes for coiled tubing and flowline applications	Hydril, Amoco, Shell, Phillips, Mobil, Elf Atochem, Dow chemicals, CEAC	5.015
Joining/Fitting for Pipes	Develop and qualify fittings for offshore GRP pipes.	Specialty Plastics, NASA	2.867
Intelligent Flexible Pipe	Develop and qualify flexible composite pipe with built-in performance monitoring for use in oil and gas production	Wellstream	5.760

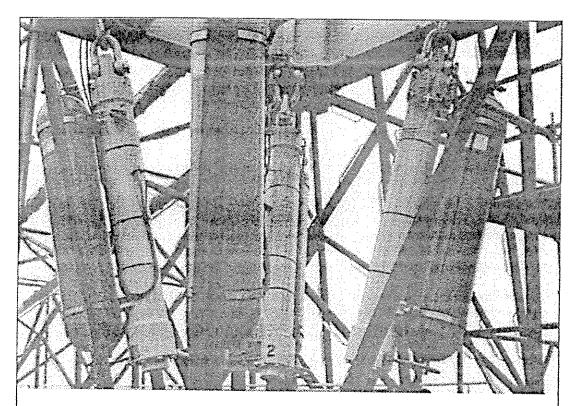


Figure 1: Composite Accumulator Bottles (Pressure Vessels) for Production-Riser Tensioning System (Lincoln Composites)

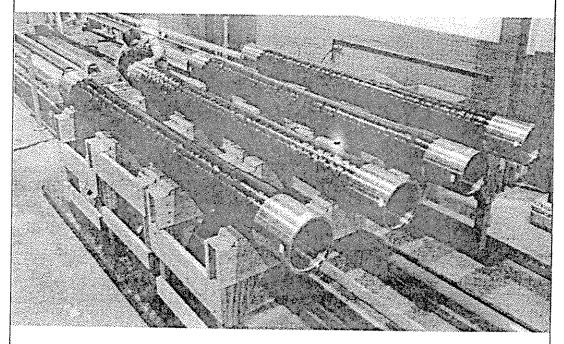
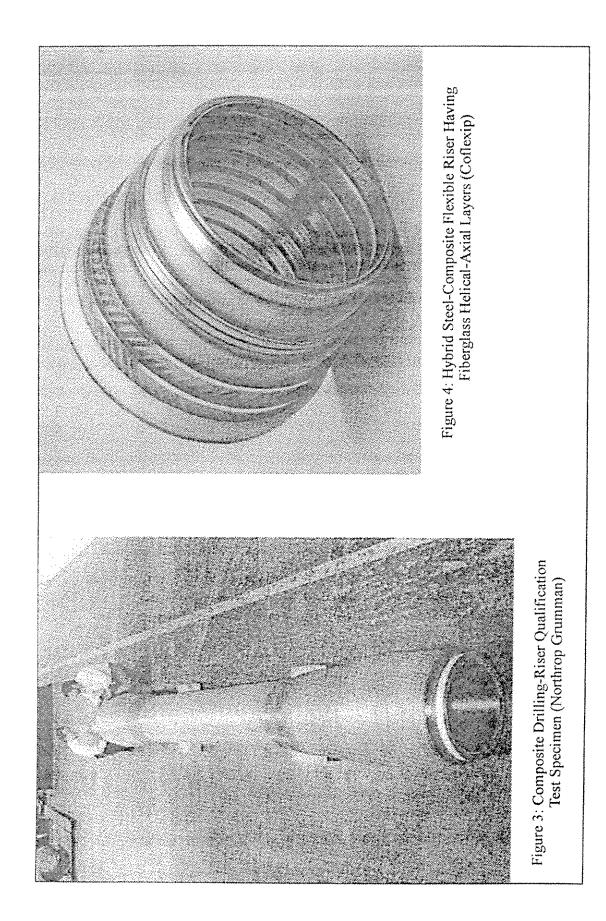
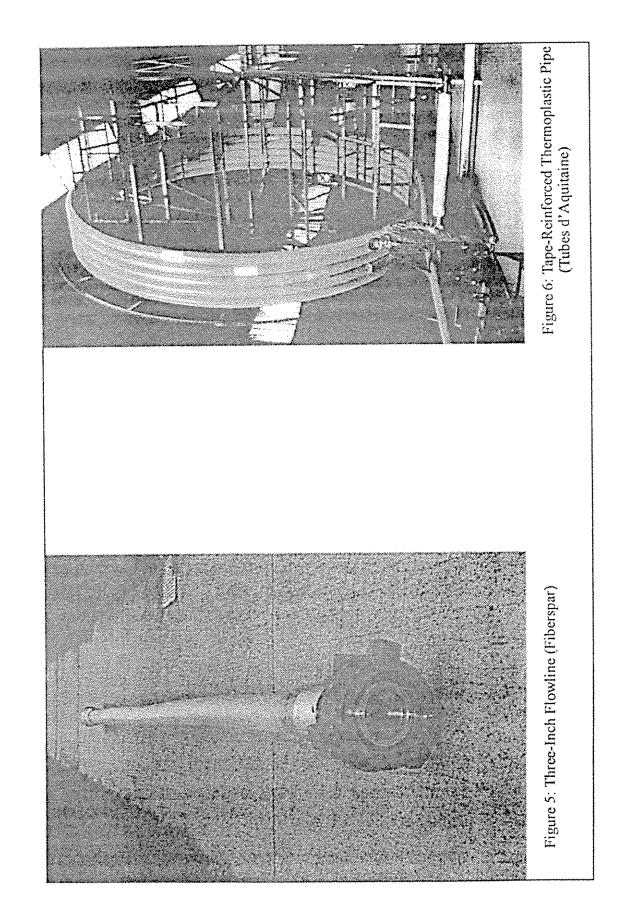


Figure 2: Composite Production-Riser Qualification Test Specimens (Lincoln Composites)







OTC 8666

Composite Production Riser Dynamics and Its Effects on Tensioners, Stress Joints, and Size of Deep Water Tension Leg Platforms

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ABSTRACT

Composite production riser (CPR) joints are being seriously considered in the development of deep water tension leg platforms (TLPs), because of their inherent light weight, superior fatigue and corrosion resistance, and outstanding specific strength and stiffness properties. Current efforts on the development of CPR joints have been mainly focused on low-cost manufacturing and failure strength evaluation of CPR tube body and CPR joint connection. The important issue of system dynamics of TLPs containing multiple CPR strings, has not been addressed.

In this paper, system analysis of a TLP containing 16 CPR strings and 12 tendons subjected to Gulf of Mexico environment loading have been conducted. The riser system is configured for 3,000 ft water depth with CPR joints, standard steel riser joints, splash zone joints, stress joint, and top tensioners. The study embraces several disciplines, including naval architecture, riser dynamics analysis, and composite failure mechanics to develop an iterative algorithm for evaluation of the top tension and stress joint requirements. Specifically, optimum top tension requirements have been determined based on riser dynamics and the failure envelope of the CPR joints. For comparison, the optimum top tension requirements are further used to size the TLPs with all-steel riser and with CPR. Computations indicate that for a water depth of 3,000 ft, unit weight reduction of the riser results in 3.31 times reduction in the TLP size. It is demonstrated that the weight reduction in the riser string is nonlinearly related to the tensioner requirement and TLP size.

INTRODUCTION

Composite materials offer many advantages for deep water applications because of their excellent corrosion and fatigue performance, high strength-to-weight ratio, and design flexibility. As the offshore industry moves aggressively to pursue deeper water developments, composite materials are finding a wide range of new applications for both topside and subsea structures. While most of the current applications are secondary structures in the top side facilities, several major U.S. and international initiatives are underway to develop primary load-bearing system components [1-6]

In deep water exploration and production, significant advantages may be realized when composite materials and structures are incorporated in the offshore system design strategy during conceptual and pre-engineering stages. For a TLP, the effective use of light weight composites may result in a significant cost savings and, perhaps, also enabling benefits. Synergistic reductions in the deck loads, hull, tendon mooring system, and platform size account for the reduced topside facilities weight [2].

This study couples fundamental failure mechanics of composites, dynamic analysis of the composite riser strings, and naval architecture to size the TLP structure. It is demonstrated that an integrated interdisciplinary effort is required to overcome technological barriers in the utilization of composite materials in the offshore industry and effective TLP design.

COMPOSITE PRODUCTION RISER JOINTS

CPR joints are currently being developed in a major project jointly supported by the industry and DoC NIST/ATP. The tube body of the CPR joint is a hybrid material system design in which the axial load is carried by helical carbon-fiber plies and hoop pressure is carried by both carbon and glass fibers wound close to the hoop direction. The detailed laminate structure of the CPR tube body is schematically illustrated in Fig. 1 [4]. The design is mainly based on load-bearing fiber strength and leakage prevention by liners. Leakage is caused by through-the-thickness matrix. Some of the initial design parameters of CPR joint are summarized in References 4 and 5. Metal inserts are placed at each end of the CPR joint to facilitate CPR joint connection. The metal fitting inserts are

joined to the CPR tube body through a trap-lock metal-to-composite interface (MCI) developed by Lincoln Composites [4].

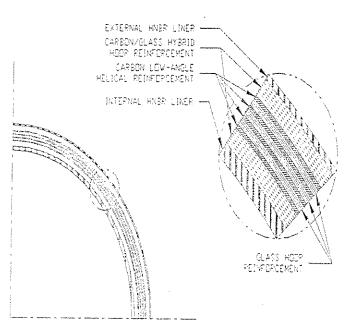


Figure 1: Laminate structure of the NIST composite production riser joint [4].

RISER SYSTEM CONFIGURATION AND DYNAMIC ANALYSIS

A commercially available three-dimensional frequency domain analysis program, FREECOM 3D, is utilized to analyze the dynamic response of the riser system. Riser configuration for 3,000 ft water depth is presented in Fig. 2. A stress joint is placed at the seabed to accommodate high bending. To further protect the CPR joints from the bending load, a transition joint and a steel riser joint is placed after the stress joint. The CPR joints are placed in the middle of the riser string where the dynamic load is predominantly in the axial direction. The riser section in the splash zone is also susceptible to bending stress due to surface events. The CPR section is terminated at 272 ft below the water level.

The same configuration is used to compare the top-tension requirements of an all-steel riser string with that containing CPR joints. In essence, the all-steel riser configuration has the same components, except that the CPR joints are replaced with standard steel riser joints.

The riser joints are modeled with 2-node tube elements with 6 degrees of freedom per node. It is important to note that the anisotropic nature of the CPR joints can not be included in the riser analysis software because of its current formulation. The CPR joints are assumed to have uniform geometry and material properties, such as unit weight, outer diameter, equivalent effective axial stiffness EA, etc. All

degrees of freedoms are constrained at the bottom of the riser string. Tensioner loads are applied at the top by spring elements. The surface tree is modeled with a mass element at the end of the riser string.

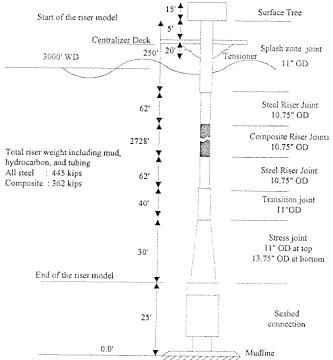


Figure 2: TLP riser configuration for 3,000 ft water depth

ENVIRONMENTAL AND OPERATION CONDITIONS

The riser dynamic analysis is performed only for the case of extreme environmental loading. The current profile and wave parameters are summarized in Table 1. These conditions represent 100-year hurricane loading in the Gulf of Mexico.

A total of 16 composite production risers are used in the dynamic analysis of the TLP. A single riser casing configuration with production tubing is used for all production risers. The production tubing is filled with hydrocarbons of 44.89 lb/ft³ density. The riser annulus is filled with mud with 97.25 lbs/ft³ density. The riser loads are calculated for a TLP excursion of 10% of the water depth. The TLP excursion, current, and wave are aligned in the same direction.

Sea Conditions		Current Profile	
Maximum Height (ft)	72.	Water depth (ft)	Current speed (knots)
Significant Height (ft)	40	Surface	3.4
Maximum Period (sec)	13.5	109	2.6
Mean Zero-Cross (sec)	11.5	280	0.0
Peak Period (sec)	14.2	3,000	0.0

ALGORITHM FOR TOP-TENSION REQUIREMENT CALCULATION

A numerical procedure is developed to determine top-tension requirements of the TLP production risers containing the CPR joints. In the numerical algorithm, composite failure mechanics is coupled with a TLP sizing study and dynamic riser analysis. A flowchart of the entire analysis algorithm is summarized in Fig. 3. At the onset of the iterative procedure, the weight of the riser string components is used to estimate an initial top-tension requirement value. Based on this initial top-tension requirement, the TLP size and corresponding response amplitude operators (RAO's) are calculated. Upon determination of the TLP RAO's, an updated tensioner requirement is determined using the von Mises stresses in the steel risers and the failure modes of composite risers. Although it is not considered in this algorithm, this stage of the riser analysis is suitable to further optimize the riser components, such as stress joint dimensions, CPR joint locations, etc. The updated top-tension value is then used to re-size the TLP. The algorithm is repeated until a tolerance limit is reached between the top-tension requirement and the TLP size.

Obviously, numerous issues need to be addressed to determine the optimum riser tensioner requirements. Owing to the space limit of this paper, only few critical design issues, such as stress joint strength, CPR strength, and pre-tensioning requirements, are addressed. Furthermore, the environmental loading conditions are also simplified. The methodology can be extended to address other critical issues, such as VIV loading, riser clashing, riser fatigue, and optimization of the riser configuration.

TLP SIZING

The TLP sizing study has been conducted based on typical Gulf of Mexico environment, number of production risers, and the deck payload level. The major constraints considered in developing the TLP configuration are summarized in Table 2.

TABLE 2: TLP SIZING PARAMETERS

Maximum tow-out draft

Minimum stability during marine operations (e.g., tow out)

Maximum column height in terms of construction lifting;

Minimum pontoon/total displacement ratio for structural integrity

Minimum riser spacing

Maximum tendon size (diameter) that can be fabricated

Maximum tendon pipe wall thickness in terms of installation Minimum tendon pipe wall thickness for structural strength Minimum natural periods

Avoidance of slacking tendons in the 100-year design event Sufficient ballast capacity for tendon tension management.

In this study TLP sizing is based on 16 production risers and 12 tendons (4 legs with 3 tendons per leg). The outer diameter and wall thickness of the steel tendon pipes are 30" and 1.25", respectively. The tendons are designed according to the API RP 2T specifications, including maximum/minimum tendon tensions [8]. Unity checks are also performed and allowances are made to accommodate higher-order tendon tension contributions. The total ballast, including that for tension management and ballast contingency, is kept at 10% of the displacement during sizing, which is adequate at this level of conceptual design.

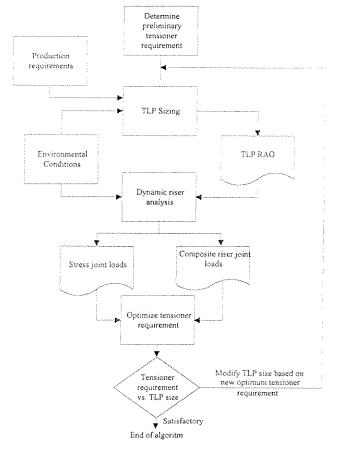


Figure 3: Top-tension requirement optimization algorithm.

The essential performance requirement of a TLP lies in maintaining its low natural period for the vertical modes of motion when subjected to design sea states. As the water depth increases, the length of the tendons, which is roughly equal to the water depth, also increases. To maintain the same stiffness, the tendon cross-sectional area has to be increased proportionally. This leads to the well-known vicious design spiral between the tendon diameter and the tendon hoop stress when the tendons are designed to be more or less neutrally buoyant. Bearing in mind the maximum tendon size that most yards are now capable of fabricating and the commonly considered deck payload level, the limiting water depth for which a TLP remains cost-effective with the use of conventional tendons is said to be about 4,000 ft. For a deeper water application, alternative tendon concepts may have to be explored. Possible alternatives are composite materials with high specific stiffness and strength, pressurized tendons, stepped tendons, and pipe/wire tendons with wire ropes for the lower portion and steel pipes for the upper portion.

FAILURE MECHANICS OF CPR TUBE BODY

Since the wall thickness of a CPR joint is small compared to its diameter, the classical lamination theory for composite laminate shell, including material nonlinearity, is used. The formulation for evaluating deformation and in-plane stress of the composite tube can be greatly simplified [9]. An instant unloading model for composite plies with progressive matrix cracking is also employed. Composite ply properties used in the analysis are summarized in Table 3.

By applying axial tension and bending, respectively, effective extensional and bending stiffnesses of the CPR joint can be calculated. The effective tensile stiffness (EA) for the CPR joint is 139×10^3 (kips) and the effective bending stiffness (EI) is 2.02×10^6 (kips-in²).

Unlike a monolithic material, a composite laminate may not necessarily lose its load-bearing capacity upon formation of matrix cracking in the individual plies. Matrix cracking causes a stress redistribution in the CPR laminate and inevitably reduces the CPR tube body's stiffness. Fig. 4 shows the effect of matrix cracking on the axial stiffness of a CPR tube body under axial tension. It is found that matrix cracking in hoop composite plies may reduce the CPR tube body axial stiffness as much as 22%. Although matrix cracking is allowed in the CPR tube body, it is desirable to configure the riser system to minimize the high axial loading during service. Proper configuration of a riser string would reduce the axial load on the CPR joints and microcracking in the CPR tube body, thus, improving the CPR failure strength. Microcracking of the composite plies may be used as a criteria in optimization of the top-tension requirement, demonstrated in the results section.

TABLE 3:	PLY ME	CHANIC	AL PROP	ERTIES (OF CPR
Elastic property	E-glass /epoxy	Carbon /epoxy	Failure Strength	E-glass /epoxy	Carbon /epoxy
E _{II} (Msi)	6.53	20.3	σ(+) Ksi	110	236

E ₂₂ (Msi)	1.81		g (-) Ksi	100	170
G ₁₂ (Msi)	0.8	0.68	Ksi Ksi	6.8	4.21
G ₁₂₁₂ (Ksi)	37,42	39	£ Ksi	22	12
			<i>பு</i> க _{ற√} Ksi	10	7.5

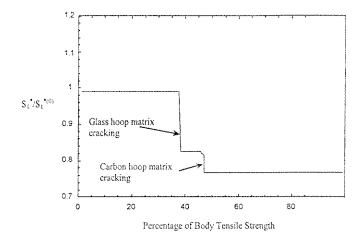


Figure 4: Tensile stiffness of CPR (Body tensile strength 1280 kips, $\mathbf{S_1}^{(0)}$ = 139000 kips.

FAILURE MECHANICS OF CPR JOINT CONNECTION

The performance of a metal-to-composite interface (MCI) under service loading is of significant concern in the CPR joint design. The current NIST/ATP CPR effort has led to the development of an advanced MCI using the well-known traplock configuration [4,5]. A performance envelope of the MCI, reported in [4], is presented in Fig. 5 [3]. In this study the MCI strength results presented in Fig. 5 are used to demonstrate the performance of the MCI in comparison to the other critical factors in the riser design. For illustration, simulations in this study are conducted for the low internal pressure, where the axial load capacity of the MCI is around 800 kips.

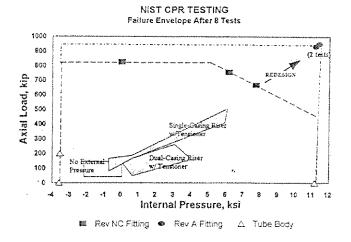


Figure 5: Apparent failure envelope of metal-to-composite

interface of the composite production riser joint [4].

RESULTS

Dynamic Riser Response Simulations: Fig. 6 presents the variation of axial loading along the riser for a top-tension of 532 kips. The axial load along the riser string is maximum at the top and monotonically decreases with water depth. One of the condition for top-tension requirement is to eliminate the compressive axial load at any location along the riser string. A tensile axial stress along the riser can be assured by applying a large tensile load. The most critical locations are 1) at the bottom of the riser string where the tensile load is minimum, an axial load needs to overcome the bending at the riser base, and 2) in the top CPR joints where the axial load is maximum, the axial loading governs failure of the CPR tube body and the MCI.

Fig. 7 presents the accompanying bending variation along the riser string. The bending moment is maximum at the bottom and rapidly decreases in the stress joint. The CPR joints are placed in the middle of the riser string such that they are subjected to minimal bending loads. The bending moment also escalates in the splash zone due to the effect of surface events. However, for the environment considered, the bending moment at the stress joint is considerably higher than that in a splash joint.

Fig. 8 presents the change of the von Mises stress along the riser string. In this representation the von Mises stress in the CPR tube body have no physical meaning because of the material characteristics. The dynamic riser analysis program does not account for the anisotropy of the CPR joint. However, the stresses in the stress joint and in the splash zone could be critical in determination of the top-tension requirement.

Stress Joint Design Criteria: In Fig. 9 the maximum von Mises stress along the riser, which occurs in the stress joint, is plotted against top-tension. The von Mises stresses in the stress joint are traced at two locations. Location A is always at the riser base. When the riser tension is low, excursion of the vessel causes a bending load a the riser base, leading to a high von Mises stress. Excessive bending at the bottom can be compensated by increasing the top-tension. However, increasing the top-tension also increases the axial stress component of the von Mises stress. Since the stress joint is tapered, a location, which changes with the top-tension value, near the top of the stress joint could also experience a high stress. The stress at this location is indicated by B. As

anticipated, there is a crossover between the curves A and B. From stress joint design considerations a proper top-tension value can be selected based on these curves. The stress joint design may also be optimized by modifying the stress joint geometry and material properties, which is currently not considered as part of the riser system configuration optimization procedure.

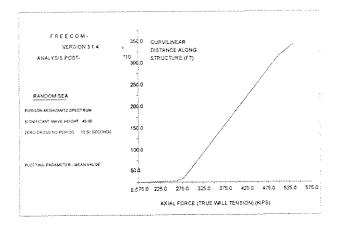


Figure 6: Variation of axial tension along the riser. Riser configuration with 16 composite production risers, top-tension = 532 kips.

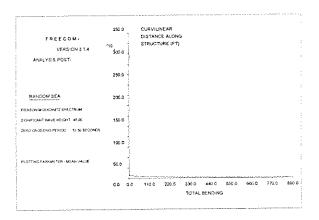


Figure 7: Bending moment variation along the riser length. Riser configuration with 16 composite production risers, top-tension = 532 kips.

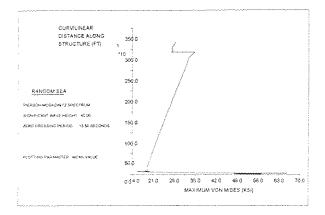


Figure 8: Maximum von Mises stress variation along the riser length. Riser configuration with 16 composite production risers, to-tension = 532 kips.

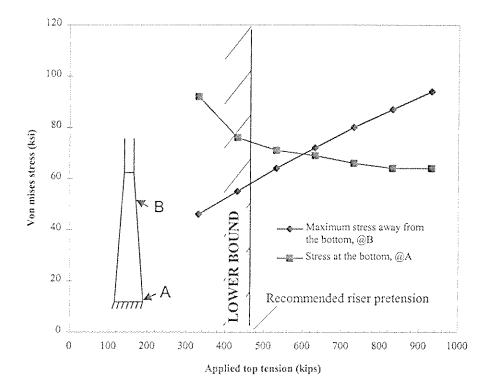


Figure 9: von Mises stress variation with top-tension in the stress joint. Riser configuration with 16 composite production risers, top-tension=532 kips. Location A is always at the bottom of the stress joint. Location B is the maximum von Mises stress away from the bottom.

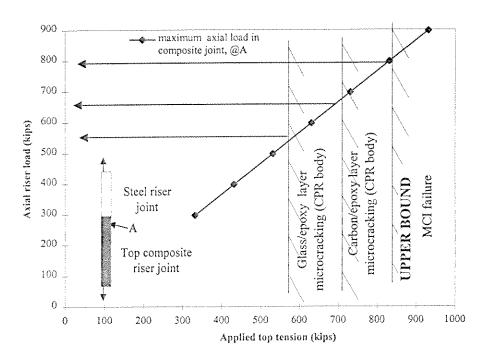


Figure 10: Axial force variation with top-tension near the top composite production riser string.

Upper and Lower Bounds of Top-Tension Requirement:. Since a compressive load is not allowed at any location along the riser string in the top-tension riser design, at the very minimum top-tension should be greater than the riser weight. Production risers in a TLP are typically pre-tensioned to 1.3 times their weight. This value is indicated as the "lower bound" of the top-tension requirement in Fig. 9.

The CPR joints are placed at a location where the axial stress dominates the riser performance. As indicated in Fig. 6, the highest axial load along the riser string occurs at the top CPR joints. In Fig. 10 variation of axial load at the top CPR joint with top-tension is presented.

The CPR joints are subjected to a multitude of deformations and failure mechanisms. The CPR joints under axial loading may fail in a tube body or at the MCI. Based on the data presented in Fig. 4 and Fig. 5, some of the critical design issues are illustrated in Fig. 10. Since application of the tensioner load is close to the top of a riser string, with respect to the overall riser length, the tensile load in the top CPR joint is very close to the tensioner load, with a slight change due to surface waves and currents. The top-tension corresponding to microcracking in the CPR tube body, glass/epoxy and carbon/epoxy plies, and MCI failure are indicated. Note that microcracking of the CPR tube body occurs earlier than the MCI failure. The "upper bound" for the top-tension requirement is obviously governed by the MCI strength.

Impact of Top-Tension on the Riser Failure Modes: All of the design issues considered in this study are combined in Fig. 11. The pre-tensioning requirement drives the lower bound of the top-tension. Note that the lower bound is dependent on the riser weight. The upper bound for the top-tension appears to be the strength of the MCI. As the riser is configured for deeper waters, the lower bound increases. On the other hand, the upper bound is a strength property of the CPR joint which does not change with water depth. Consequently, for a deeper water configuration the difference between the upper and lower bound decreases. This would limit the room for toptension optimization in a deeper water riser configuration. Apparently, when the lower bound reaches the upper bound the riser configuration is no longer feasible. The difficulties in the top-tension operation zone can be alleviated by placing CPR joints farther below the water surface where the axial loads are smaller, such that the upper bound can be further increased.

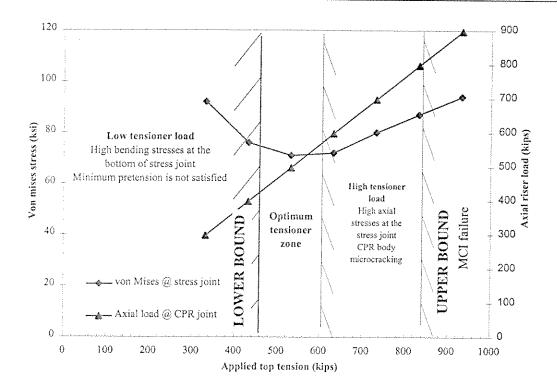


Figure 11 Failure modes and design criteria which govern top-tension requirement, Riser configuration with 16 composite production risers joints, 3,000 ft water depth.

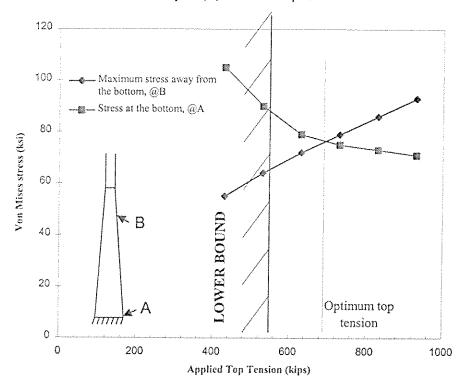


Figure 12 Design criteria for top-tension requirement. Riser configuration with all-steel riser joints, 3,000 ft water depth.

For the present configuration the applied top-tension imposes several classes of design issues, as shown in Fig 11. Five regions of failure mechanisms may be considered: low tensioner load, optimum tensioner load, glass/epoxy composite microcracking, carbon/epoxy composite microcracking, and the MCI failure. For a low pre-tension, a high bending stress in the stress joint is most critical and the minimum pretension requirement is not satisfied. An optimum top-tension requirement region exists in this configuration. From the stress joint considerations, the optimal top-tension may occur at the high end of this region. However, competition between the weight penalty paid for higher tensioner capacity and the stress in the stress joint must be considered in selection of the top tension requirement. A smaller design spiral may be suitable to further optimize the top tension requirement in this region. The next region is designated as high tensioner-load region. In this region the CPR tube body is susceptible to microcracking and damage accumulation which may lead to long term stiffness and strength degradation. This region can be further divided into two, based on carbon/epoxy and glass/epoxy layer microcracking resistance. It is desirable to avoid this region by proper configuration of the riser system and proper selection of the tensioner capacity. Finally, the upper bound of the riser configuration is governed by the MCI failure. For the cases under high axial loading, the failure strength of the CPR tube body is greater than the MCI strength. Note that, for combined axial and pressure loading cases the failure modes may be different, as depicted in Fig. 5.

Top Tension Requirement for All-Steel Riser Configuration: The top tension requirement for an all-steel riser configuration is also calculated, using the same methodology. In this case simple failure modes leads to fewer top tension requirement regions, as illustrated in Fig. 12. The lower bound is determined by the riser pre-tensioning

requirement, whereas the upper bound depends on the capacity of the API connector. The critical location for the all-steel riser configuration is in the stress joint. Since the lower bound and upper bound for the all-steel riser configuration are far apart, the tensioner load corresponding to the minimum von Mises stress in the stress joint may be used as for proper design purpose.

Impact of Tensioner Requirement on TLP Size: The impact of aforementioned top tension requirement on the TLP size is illustrated in Fig. 13. It is demonstrated that the TLP size is not linearly dependent upon the top tension requirement. For a small tensioner loading, less than 500 kips, the impact of change in the tensioner capacity requirement to TLP size is smallest. Each pound saved in the tensioner requirement is reflected by approximately 1.33 times to the TLP size. In this study the top tension requirements for the composite and allsteel riser configurations are in the medium tensioner capacity range, where reduction in the tensioner capacity is reflected on the TLP size by approximately 1.75 times. The results from the optimization procedure suggest that the optimum top tension for the all-steel configuration is 710 kips, and for the composite riser configuration is 560 kips. Reduction of 150 kips in top-tension equals to 275 kips weight reduction per riser which is 4,400 kips of total weight reduction. In other words, when the top tension is decreased from 710 kips for all-steel riser to 560 kips for a CPR on a 16-riser TLP, the deck payload capacity would be increased by 2,200 short tons, a very significant increase in the cost/per deck payload. The impact of the top tension requirement for a higher capacity tensioner configuration, e.g. deeper water applications, is expected to be more dramatic. For the top tensioner requirement greater than 700 kips, the tensioner requirement is magnified by approximately 2.11 times when considering TLP sizing.

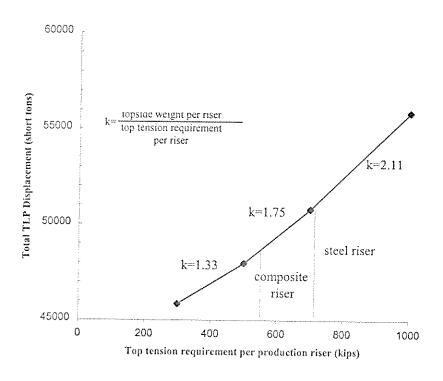


Figure 13: TLP displacement as a function of tensioner requirement for a production riser.

CONCLUSIONS AND ADDITIONAL REMARKS

Based on the results obtained, the following conclusions may be reached:

1. The impact of reduction in the riser weight and tensioner capacity requirement to the TLP size is quantified. The comparisons in weight saving are summarized in Table 4.

In the current 3,000 ft water depth configuration, the riser weight and tensioner requirement can be reduced by 83 kips and 150 kips, respectively, by introducing CPR joints in the riser string. For a typical 16-well configuration TLP, the total weight reduction is estimated as 4,400 kips. With a reduction in riser weight and tensioner requirement, the TLP can be increased by 3.31 and 1.83 times, respectively. For deeper water riser configurations potential for TLP size reduction is greater simply because more CPR joints can be placed in the riser string

TABLE 4: TI	LP WEIGHT SA	VING SUMMA	ARY
	Riser weight (kips)	Tensioner requirement (kips)	TLP size (short tons)
All-steel	445	710	51,000
Composite	362	560	48,800

Difference	83	150	2,200
	ΔTLP size	2,200 * 2	
ΔTei	isioner Requir	ement 150*16	= 1.83
Δ:	TLP size 2,3	200 * 2	
ΔRis	er Weight 8	$\frac{200 * 2}{3 * 16} = 3.31$	

- To determine accurately the cost benefits and enabling capabilities of introducing CPRs into a TLP, an interdisciplinary study, involving riser dynamics analysis, naval architecture, and composite mechanics/design is necessary.
- 3. Numerous factors need to be considered in determination of the top tensioner requirements of TLP production risers. In addition to the design parameters and failure modes considered in this study, issues such as vortex induced vibration and riser clashing needs to be considered in a wide range of loading scenarios. In this study the dynamic riser analysis is conducted for the case of 100 year hurricane loading.
- 4. The riser axial strength and the metal-tocomposite joint performance remains to be improved. The CPR tube body's axial strength is

higher than the MCI strength in the high axial loading cases. However, when the CPR joint is loaded in the axial direction, degradation and damage of the CPR tube body occurs progressively as the individual plies has different strengths. Advanced long-term strength prediction methodologies must be developed to optimize the materials and lay-up sequence in the composite riser tube body.

5. The potential economic and performance advantages of using composite materials for coupled TLP riser tension and construction are significant. The light weight of such tendons made of composite materials may directly translate into more effective reduction in top tension and, therefore, the TLP size or equivalently, into increase in a TLP payload capacity. The higher stiffness of the composite tendons will make natural periods of the TLP motion in the vertical plane much less sensitive to water depth increase.

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Composite Production Riser Reliability Assessment: The Influence Of Probabilistic Fiber-Composite Strength

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Abstract

The important issue of the influence of probabilistic fiber composite strength on the reliability assessment of a composite production riser is studied. Based on composite micromechanics, the probabilistic strength function of a fiber composite is formulated to include the fiber strength statistics. The strong anisotropy in composite strength requires the statistical strength theory of fiber composites be developed for a composite production riser (CPR) subjected to general multiaxial loading. A probabilistic failure model, based on progressive damage and failure composite plies, has been constructed for CPR's with hybrid composite construction. An efficient computational procedure has been established, using a coupled nonlinear composite laminate shell stress analysis and the probabilistic failure model developed, for conducting rigorous CPR reliability assessment. Numerical solutions have been obtained for the CPRs designed and constructed for a TLP in 3,000 ft water subjected to the environmental loading specified in the NIST ATP Composite Production Riser Project. The results show that the CPR reliability is strongly governed by the statistical strength distribution functions of constituent load-bearing fibers and also by matrix cracking characteristics in the hybrid CPR system.

1. Introduction

A production riser is a critical load-bearing tubular structural component which extends the well bore from the sea floor to a surface platform. A primary function of the riser is to

accommodate the production tubing which is a fluid conduit to the reservoir. Additional functions of a production riser include accommodating well control hardware and facilitating well completion and workover operations. Composite production risers (CPR's) are currently seriously considered in the present deepwater E & P development because of their advantages of light weight, excellent corrosion resistance, superior fatigue characteristics, and Current studies [1, 2] have great design flexibilities. indicated that introduction of composite production risers in a deepwater TLP system will result in, among other advantages, significant weight reductions, lower top tensions, and reduced These would lead to loads in the bottom stress joints. effective cost savings, simplifications or elimination of tensioners and riser handling systems, reduced platform deck loads, and reduced design requirements of seabed stress

From 1979 to 1989, the Institut Français du Pétrole (IFP) and Aerospatiale conducted extensive developmental studies [3, 4] on high-performance fiber-composite tubes up to 9-inch diameter for offshore E & P industry applications. The efforts included manufacturing, mechanical testing, aging and environmental degradation assessment, proof-of-concept composite riser tests, and damage tolerance evaluation. The IFP's composite riser work did not eventually result in an acceptable and qualified composite production riser for offshore E & P operations. A primary reason for this is that reliability of the CPR was not fully established.

Without overcoming the reliability issues, composite production risers would not be qualified, and thus could not be confidently accepted in design and construction of deepwater production systems, as the financial and safety consequences of a riser failure are too severe. Obviously, a comprehensive reliability assessment of the composite production risers involves many components, such as uncertainties, risk, and economics. Probabilistic methods have been recommended to assess the reliability of fixed-leg steel platform structures [5]. In a CPR reliability assessment,

composite production riser has been introduced in the current CPR development [23]. The testing program has been designed to develop a performance data base for qualifying the CPR component. In addition, the testing program, combined with an advanced analytical effort, is intended to establish a guideline and procedure for future design of CPR's with different sizes in other operating conditions.

3. Objectives

The objectives of this paper are to:

- (1) Develop a statistical strength theory for anisotropic fiber composites subjected to multiaxial loading.
- (2) Construct a probabilistic failure model for composite production risers with hybrid composite system construction under combined axial loading and pressure.
- (3) Establish an efficient computational procedure to conduct reliability assessment of composite production risers under prescribed loading.
- (4) Demonstrate the effectiveness of the developed analytical methodology for riser reliability by studying the current NIST ATP CPR Design 6.1 case.

4. Method of Approach

- **4.1 Stress Analysis of Composite Production Riser Tube Body.** The following assumptions on the CPR material and geometry are introduced in the current analysis of a composite production riser tube body:
- (1) Ply composite material properties of a CPR tube body are cylindrically anisotropic with a strong shear nonlinearity.
- (2) Bending on the CPR is small and negligible.
- (3) The diameter of a CPR is small compared to its length.

As shown in Fig. 4.1, a CPR tube body is considered to be a long cylindrical, composite laminate shell with cylindrically anisotropic ply properties subjected to combined internal pressure and axial tension. The constitutive equations for each ply composite are

$$\sigma_i = Q_{ij}(\sigma_6)\varepsilon_j \qquad (i, j = 1, 2, 6), \tag{4.1}$$

where ε_j and σ_i are ply strains and stresses in material coordinates. The Q_{ij} is anisotropic stiffness matrix of the ply composite.

In Eq. (4.1), the composite is assumed to behave linearly along its principal material directions. In shear, however, a nonlinear ply constitutive equation is employed, since glass/epoxy and carbon/epoxy are known to exhibit severe shear nonlinearity. The nonlinear shear deformation may be expressed as

$$\gamma_6 = 2\varepsilon_6 = S_{66}\sigma_6 + (S_{6666}\sigma_6)^3$$
 (4.2)

where γ_6 is the engineering shear strain, and S_{66} and S_{6666} are linear and nonlinear shear components, respectively.

A classical lamination theory for thin composite shells is used to determine the ply stresses in a CPR when subjected to combined internal pressure and axial loading. The theory embodies a collection of stress and deformation assumptions [24]. Based on these assumptions, laminate stiffness equations for thin filament-wound composite can be determined from ply constitutive equations, Eq. (4.1), fiber orientations and stacking sequence, and are given as follows:

$${N \atop M} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} {\epsilon^{0} \atop \kappa}$$
(4.3)

where N and M are resultant forces and moments. The ϵ^0 and κ are mid-surface strains and curvatures. The A, B and D are well-known extensional, coupling and bending stiffness matrices, respectively, for a composite laminate shell [25] in global cylindrical coordinates.

Note that Eq. (4.3) represents a nonlinear load-deformation relationship for the composite laminate riser body, since A, B and D matrices are functions of the shear stress in each ply. The ply stresses in a composite production riser tube body may be determined by using the procedure proposed in [25] with the aid of an iterative algorithm as shown in [26].

4.2 Property Degradation Approximations and Evaluation. Mechanical properties of the composite laminate in a CPR may degrade as internal damage accumulates during the load increase. A number of progressive failure theories have attempted to address the ply failure progression in a composite laminate. A common feature of the progressive failure theories is that proper ply unloading would take place after the ply fails. In this study, an instantaneous unloading model is used in progressive failure analysis. The model is conservative, which assumes that a composite ply loses its load-carrying capacity immediately after the ply fails. Furthermore, for simplicity without loss of generality, the well-known maximum stress failure criteria are used for both fiber- and matrix-dominated modes of ply failure.

4.3 Probabilistic Formulation of Damage and Failure of Fiber Composites. In general, failure probability $P_{\rm f}$ of a composite riser tube body subjected to external loading may be expressed as

$$P_{f}\{CPR \mid Tube \mid Body\} = P_{f}\{\bigcup_{i=1}^{n} \widetilde{M}_{i}\}$$
 (4.4)

where \widetilde{M}_i is the i-th mode of failure and n is the total number of failure modes involved. Also, the composite riser tube body failure in a particular i-th mode may be schematically related to a local ply material damage mode as

Since carbon fibers are used mainly to carry the axial load, the probability of axial ply failure may be expressed in term of ply fiber breakage and matrix fracture as

$$P_{f}\{Axial\} = P_{f}\{\{\bigcap_{i=1}^{r} M_{j_{c}}^{cfa}\} \cap \{\bigcap_{i=1}^{s+t} M_{j}^{mch}\}\}$$

$$(4.14)$$

where $M_{i_c}^{cfa}$ represents carbon-fiber failure in the j_c -th ply under biaxial loading. M_i^{meh} denotes matrix cracking in the j-th hoop ply, and r, s, t are numbers of the specified axial carbon-fiber composite layer, hoop glass-fiber composite layer, and hoop carbon layer, respectively. The right-hand-side of Eq. (4.14) may be expressed as

$$\begin{split} & P_{f}\{\{\bigcap_{j_{c}=1}^{r}M_{j_{c}}^{cfa}\} \cap \{\bigcap_{j=1}^{s+1}M_{j}^{mch}\}\} \\ & = P_{f}\{\bigcap_{j_{c}=1}^{r}M_{j_{c}}^{cfa}\}P_{f}\{\bigcap_{j=1}^{s+1}M_{j}^{mch}|\bigcap_{j_{c}=1}^{r}M_{j_{c}}^{cfa}\} \\ & = P_{f}\{M_{1}^{cfa}|\bigcap_{j_{c}=2}^{r}M_{j_{c}}^{cfa}\}P_{f}\{M_{2}^{cfa}|\bigcap_{j_{c}=3}^{r}M_{j_{c}}^{cfa}\} \\ & \cdots P_{f}\{M_{r-1}^{cfa}|M_{r}^{cfa}\}P_{f}\{M_{r}^{cfa}\}P_{f}\{\bigcap_{j=1}^{s+1}M_{j}^{mch}|\bigcap_{j_{c}=1}^{r}M_{j_{c}}^{cfa}\} \\ & (4.15) \end{split}$$

Eq. (4.15) actually represents a progressive failure process in the evaluation of the CPR reliability, which is an important feature in the composite riser failure (i.e., in a parallel system).

In the current CPR design [6], both glass fibers and carbon fibers are employed in the near hoop-wound layers to resist the internal pressure. They form a parallel system with the failure probability expressed as

$$P_{f} \{ \text{Hoop} \} = P_{f} \{ \{ \bigcap_{j_{c}=1}^{t} M_{j_{c}}^{\text{cfh}} \} \cap \{ \bigcap_{j_{g}=1}^{s} M_{j_{g}}^{\text{gfh}} \} \cap \{ \bigcap_{j=1}^{t} M_{j}^{\text{mea}} \} \}$$
(4.16)

where $M_{j_e}^{\text{gth}}$ and $M_{j_e}^{\text{cth}}$ represent failure of hoop glass fibers and hoop carbon fiber layers, respectively.

Since large differences exist in strength among the glass fibers, carbon fibers and the matrix, it may be appropriate to express Eq. (4.16) in the following form

$$P_{f}\{\text{Hoop}\} = P_{f}\{\bigcap_{j_{c}=1}^{t} M_{j_{c}}^{cfn}\} \{\bigcap_{j_{g}=1}^{s} M_{j_{g}}^{gfn}\} \cap \{\bigcap_{j=1}^{r} M_{j}^{mca}\}\}$$

$$*P_{f}\{\bigcap_{j_{g}=1}^{s} M_{j_{g}}^{gfn}\} \bigcap_{j=1}^{r} M_{j}^{mca}\} P_{f}\{\bigcap_{j=1}^{r} M_{j}^{mca}\}$$
(4.17)

Again, Eq. (4.17) represents a progressive failure process in 'he hybrid, near hoop-wound layers of a composite riser body. Proper evaluation of probability of the hoop ply failure requires not only progressive failure analyses of carbon and glass hoop layers individually, but also the failure analysis of

carbon hoop layers under the condition that hoop glass-fiber layers fail.

The failure probability formulation for the CPR (Design 6.1) developed above involves a complicated progressive failure probability assessment. However, when the CPR is subjected to combined internal pressure and axial tension, the stress gradient within the hoop carbon layers along the thickness direction of the tube body is small. This is also true for the hoop glass-fiber layers and the helical carbon layers. Therefore, assuming the coefficients of variation in ply strength are small for the glass and carbon reinforced plies, equations (4.14) and (4.16) may be simplified by combining all the hoop-wound carbon laminae into an "equivalent" carbon composite layer. A similar approach may be taken on the hoop glass layers and the axial carbon layers. Therefore, one has the resulting forms for P_e {Axial} and P_e {Hoop} as

$$P_{f}\{Axial\} = P_{f}\{M^{cfa} \cap M^{nsch}\}$$
(4.18)

$$P_{\ell} \{ \text{Hoop} \} = P_{\ell} \{ M^{\text{gth}} \cap M^{\text{cth}} \cap M^{\text{mea}} \}$$

$$= P_{\ell} \{ M^{\text{cth}} | M^{\text{gth}} \cap M^{\text{mea}} \} P_{\ell} \{ M^{\text{gth}} | M^{\text{mea}} \} P_{\ell} \{ M^{\text{mea}} \}$$

$$(4.19)$$

5. Computational Algorithm Development for CPR Reliability Analysis

5.1 Degradation of Composite Riser Laminates.

(1) Composite tube body matrix damage

In the case of matrix cracking in CPR tube bodies, the aforementioned maximum stress criteria are employed. Material property degradation associated with the damage requires instantaneous unloading in the computational scheme. The composite ply with matrix cracking is assumed to lose its partial load-bearing capacity. The ply stiffness matrix in the material coordinate system at a degraded ply may be modified as

$$\begin{bmatrix} \overline{C} \end{bmatrix} = \begin{bmatrix} \overline{C}_{11} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

(2) Composite tube body fiber breakage

In the case of fiber breakage in CPR tube bodies, the maximum stress criteria are also employed. Material property degradation associated with the damage requires instantaneous unloading. The composite ply with fiber breakage is assumed to lose its partial load-bearing capacity. The stiffness matrix in the material coordinate system in a degraded ply is modified as

$$[\overline{C}] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \overline{C}_{22} & 0 \\ 0 & 0 & \overline{C}_{66} \end{bmatrix}$$

- failure model development.
- (3) A probabilistic failure model, based on progressive damage and failure of fiber composite plies, has been constructed for CPR's with hybrid composite laminate systems under combined pressure and axial loading.
- (4) An efficient computational procedure has been established, based on a coupled composite riser stress analysis and the probabilistic failure model developed, for conducting accurate CPR reliability assessment under prescribed environmental loading.
- (5) The effectiveness of the analytical methodology developed has been demonstrated by a critical evaluation of the CPRs designed and constructed for a TLP in 3,000 ft water subjected to the environmental loading specified in the NIST ATP Composite Production Riser project.
- (6) The numerical results obtained from the study indicate that the composite riser reliability is strongly governed by the statistical strength distribution functions of constituent load-bearing fibers and also by matrix-cracking characteristics in the hybrid riser composite system.

8. Acknowledgment

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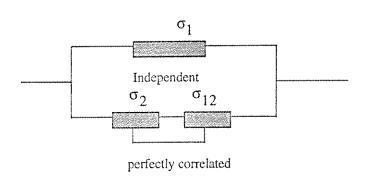


Fig. 4.2 Probabilitic Model for Fiber Composite Failure

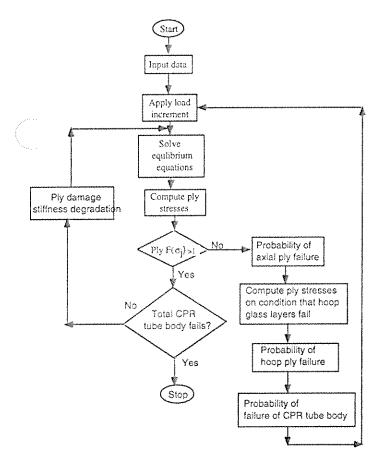


Fig. 5.1 Incremental-iterative computational algorithm for probabilitic failure analysis of composite production riser tube body

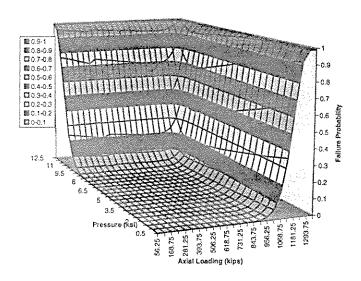


Fig. 6.1 2000-hour Failure Probability of CPR (Design 6.1) under Combined Internal Pressure and Axial Loading

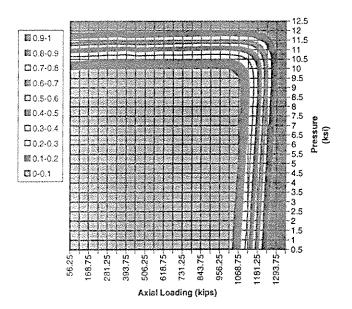


Fig. 6.2 2000-hour Failure Probability of CPR (Design 6.1) under Combined Internal Pressure and Axial Loading

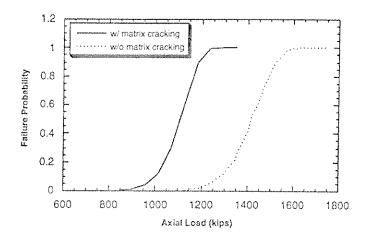


Fig. 6.7 30-year Fallure Probability of CPR (Design 6.1) under Combined Axial Loading and Internal Pressure (0.5 ksi)

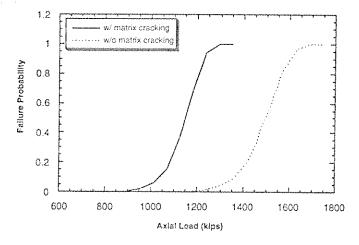


Fig. 6.8 30-year Failure Probability of CPR (Design 6.1) under Combined Axial Loading and Internal Pressure (7.5 ksi)

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KEY ISSUES IN THE DESIGN OF DEEPWATER COMPOSITE RISERS

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ABSTRACT

Composite materials offer several unique properties such as high strength-to-weight ratios and excellent fatigue and corrosion resistance that make them economically attractive for deepwater risers. To insure successful design and operation of composite risers, several key technical issues that are unique to composite components must be addressed. These issues include the interface between the composite pipe and the metal connector, internal and external damage protection, analysis methods and their validation, allowable strength parameters, manufacturing and quality control strategy. The paper reviews current practices for addressing these issues as they were applied to both composite production and drilling risers. In addition, the paper summarizes the basic performance and cost data for these risers. A brief review of recent offshore application of composite components is also presented.

INTRODUCTION

As part of the oil industry's efforts to reduce the life-cycle costs of deepwater developments and to improve reliability, considerable attention is being devoted to the evaluation and application of innovative and cost-competitive alternative materials. Advanced composite materials offer several attractive properties such as reduced weight, improved corrosion resistance, proper thermal resistance, and excellent fatigue performance. Although on a one-on-one basis components made of composites will most likely be more expensive than an identical, or functionally equivalent, steel counterpart on a performance-equated basis, the economic advantage of composite components can often be demonstrated by examining their impact on reducing system and fullcycle costs. This is achieved because composites permit greater design flexibility for tailoring structural properties to meet specific design requirements, thus promoting system simplification and achieving higher reliability. Also, new innovations are being developed to embed fiber optics and electrical conductors into the composite part to monitor structural integrity and loads during service, and to obtain operational conditions from remote locations.

Composites have been successfully used by the offshore oil industry in a variety of applications (Salama, 1997). These include storage tanks, pressure vessels, low pressure pipes, reinforcements for flexible pipes, torque shafts, structural parts, seals, gratings, fire and blast walls, cable trays, etc. The motives are lower weight, less maintenance, and reduced installation costs. Some specific examples for the offshore application of fiberglass composites include fire water piping (Amoco's Valhall, Conoco's Marquette, Shell's Mars), seawater piping (Dubai, Conoco's Heidrun, Phillips Ekofisk), storage vessels (Conoco's Heidrun,

Amoco's Davy/Bessemer), grating (Shell's Mars, Ram-Powell and Ursa), mud mats (Elf's Garibaldi C), and subsea wellhead protection (Shell's Vigidis and Draugen). High-pressure (3000 psi operating pressure) composite accumulator vessels have been used for production-riser tensioning systems on Mars, Ram-Powell, and Ursa TLPs. They are constructed of carbon/S-glass fiber epoxy composite over an HDPE liner with 316L stainless steel bosses. While the weight of these composite vessels was about 1/3 the weight of the equivalent steel vessels, the cost of the composite vessels was actually lower than the steel vessels. Composite pressure vessels have been developed and field qualified for use as mud gas separators (MGS). The primary advantages that composite MGS offer are reduced maintenance and 50% weight savings over carbon steel vessels.

Successful composite experiences, coupled with the need to reduce the life-cycle cost of deepwater development, have motivated the industry to examine the application of composites in several critical applications, particularly for water depth sensitive components such as riser pipes and riser components (taper joints, tensioners, choke and kill lines, etc.). Initial efforts focused on composite production risers because of their obvious advantage in reducing the required pretension and simplifying the riser tensioner system. During 1985 to 1989, several major oil companies joined with the Institut Francais du Petrole and Aerospatiale to develop and evaluate a 9 5/8 inch composite production riser (Sparks, 1986; Sparks, et. al, 1988). Although the project achieved technical success, it did not meet the commercial hurdles because the composite price was high.

As a follow-up to this study, Lincoln Composites suggested design changes to reduce the cost of the composite risers. These changes involved simplifying the metallic threaded joint and using the lower cost E-glass instead of the S-glass. In order to assess the effect of these changes on both performance and cost, a joint-industry project that is jointly funded by NIST/ATP was initiated in 1995. A critical element of this project was the specification and implementation of a comprehensive testing program to confirm the advantages, validate the design, and establish long-term performance of a high pressure (6000 psi operating pressure) 10% inch composite production riser. Building on the results of this project, Norske Conoco and Kvaerner initiated a joint industry project that is partially funded by EU Thermie to design, manufacture, and qualify 22 inch high pressure composite drilling riser joints. In order to confirm the advantages and secure operational staff confidence in composite risers, field testing of the composite drilling riser joint on Heidrun TLP is part of the NCAS/Kvaerner project. Due to the severity of service performance

requirements, the field qualification of composite drilling risers should pave the way for broader field applications of other risers whose performance requirements are less severe.

Using the composite production and the drilling riser projects as basis, the paper reviews key technical issues that needed to be addressed as part of these projects. These issues include the interface between the composite pipe and the metal connector, internal and external damage protection, analysis methods and their validation, allowable strength parameters, and manufacturing and quality control strategy. The paper summarizes the basic design and cost performance data for these two composite riser projects and reviews current practices for addressing these issues as they were applied to them.

STATUS OF COMPOSITE RISER PROJECTS

Table 1 provides a summary of the basic specification and the performance of NIST ATP composite production riser and NCAS/KOP drilling riser joints. Details on these projects have been discussed by Salama, Johnson, and Long (1998) and by Salama, Murali, Baldwin, Jahnsen, and Meland (1999). The weight and cost

of the composite production riser are related to equivalent steel riser joints with a premium steel connector. The cost target for the composite riser with steel premium connectors is 1.5 times the cost of an equivalent steel joint with a welded connector or 10% less than a steel riser joint with an integral connector that is machined on an upset end. The weight and cost of the composite drilling riser is related to equivalent titanium riser joints that have been used on Heidrun TLP. The composite drilling riser joint is supplied with the same titanium compact flanges being used on Heidrun. Figure 1 shows a schematic of the main features of the composite drilling riser joint. Figure 2 is a schematic of the composite production riser and Figure 3 shows prototype composite production riser joints that have been used for testing. During the design of these riser joints, several technical issues that are not common to steel risers needed to be addressed. These issues include the interface between the composite pipe and the metal connector, internal and external damage protection, analysis methods and their validation, allowable strength parameters, and manufacturing and quality control strategy. The following sections discuss the rationale that was utilized to resolve these issues.

Table 1. Comparison between Design Requirements and Predicted Joint Performance

Design Parameter	Composit	e Drilling Riser	Composite Production Riser		
Design rarameter.	Specification	Performance	Specification	Performance	
Internal Pressure, psi	6200	12.400 (min.)	6000	11,000 (min.)	
Bending, kN-m	1401	2180 (min.)	NA	NA	
Axial Load, kips	NA	NA	200	900 (min.)	
External Pressure, psi	470	2500 (min.)	2500	4000 (min.)	
Impact, kJ	50	50	5	5	
Fatigue, yrs	45	170	90	>> 100	
Tube Stiffness, EA, kips	1,124,000	940,000	100,000	120,000	
Dimensional Limits	1D = 22 inch OD < 31.1 inch L = 48.2 ft	ID = 22" OD = 25.1" L = 48.2 ft	ID = 10.05" OD = as required L = 50 ft	ID == 10.05" OD == 12" L == 50 ft	
Tube Wt. lb/ft	< 130.3 (Ti wt.)	87.3	< 55 (steel wt.)	20.6	
Joint Weight, lb	< 7.169 (Ti wt.)	5,642	< 2,900 (steel wt.)	1,350	
Cost per joint, \$	<450,000 (Ti cost)	250,000 300,000	<15,000 (1.5Xsteel cost)	14,250 – 15,250	

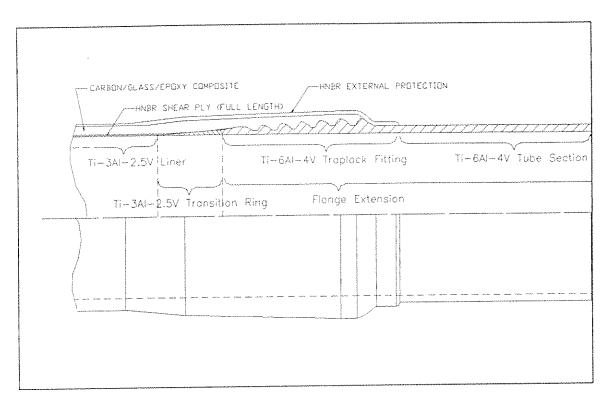


Figure 1. Schematic of Composite Drilling Riser Joint

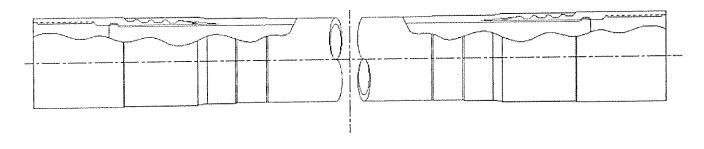


Figure 2. Schematic of Composite Production Riser Connection

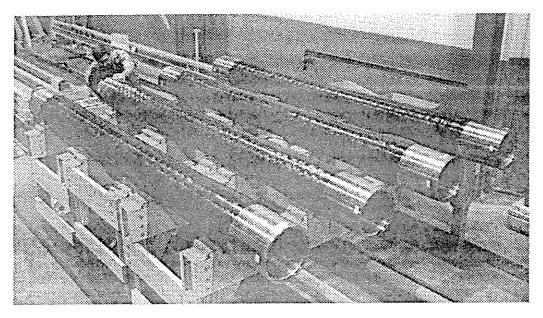


Figure 3. Photograph of Riser Specimens Used for Testing

METAL-COMPOSITE INTERFACE (MCI) FOR RISERS

The integration of composite and metal fittings is always a challenging aspect of composite structural design. The differences in material properties between the orthotropic filament wound composite and the isotropic metal end fitting impose special requirements on the selection of the manufacturing process and part design. Numerous attachment methods have been demonstrated, with a wide range and variety of load-carrying capabilities. These attachments rely on two basic approaches to provide the load transfer between the composite tube and the metallic joint. These two approaches are adhesive bonding and mechanical interlocking. In selecting an MCI option, the fabricability of the mechanical interlocking system and the long-term integrity of the adhesive bond must be considered. Mechanical locking systems include reverse taper/curve, pins, and hoop grooves. External sleeves/compression rings are sometimes considered as an additional feature to increase resistance to fiber pull of loads and to reduce bending at the tip of the metal termination. For joints that rely only on the interlocking systems, a mechanism such as a lip seal and/or o-rings must be provided between the tip of the metal termination and the composite tube to prevent the migration of internal fluids around the metal tip.

In selecting a cost-effective composite-to-metal connection for risers, it is recognized that the riser is not subjected to torsional loads. The use of traplock attachment (hoop groove mechanical locking) have been demonstrated for many composite components that are mainly subjected to axial and pressure loading. Therefore, they are considered as most appropriate for riser applications. The multiple traplock configurations illustrated in Figures 1 and 2 incorporate onepiece end fittings into each end of the composite tube during the filament winding process. Traplock joints are very cost-effective because the end fittings are manufactured with standard machine tools and tolerancing. Prior to the filament winding process, the two end fittings are installed on the filament-winding mandrel. The fittings are accurately located and held in place by specialized tooling details at each end of the mandrel. Low-angle helical layers are used to give the joint its axial strength and stiffness. These layers are wound over the end fittings and are compacted into the grooves in the fitting by winding hoop layers over them. Localized axial reinforcements can be incorporated into the trap to increase joint performance. The mechanism of load transfer in a multiple traplock varies depending on part geometry. Axial load is transferred between the composite tube and steel fitting across the trap faces. In order to achieve a good distribution of load between multiple traps, the designer must balance the relative stiffnesses of the metal and composite materials. Finite element analysis (FEA) can be used effectively for joint optimization.

DESIGN AND ANALYSIS APPROACH

An important step for design of composite risers is to define all expected failure modes, to establish the appropriate analysis strategy to predict them, and to specify proper material allowables to ensure that the component has sufficient capacity to satisfy the design requirements. The following are potential failure modes for composite risers:

- Tube body failure due to exceeding fiber tensile and/or compressive strength;
- * MCI failure due to exceeding fiber tensile and/or compressive strength;
- MCI failure due to exceeding composite interlaminar shear strength;
- * Failure of the metal components;
- Damage of the liner due to loading and/or operations;
- * Corrosion-induced failure at the composite-metal interface.

Establishing the performance limits of composite joints under all possible loading combinations using finite element analysis (FEA) involves the numerical model simulating the actual component, the analysis procedures, and the material allowables. The basic elements of the analysis approach include establishing stresses and strains at all critical positions and comparing these values with short term, long term, and fatigue allowables. Several FEA formulations are available for modeling composite materials with orthotropic properties. Nonlinear static FEA is extensively used for detailed design and analysis work.

FEA analysis of composite riser joints involves the use of two-dimensional (2-D) axi-symmetric solid models, three-dimensional (3-D) solid models, and 3-D shell models. In general, the 2-D axi-symmetric models are used to analyze and optimize MCI and tube wall geometries. The 3-D solid models are used to evaluate the performance and behavior of the riser joint under bending moments and under impact loading. Hyperelastic solid elements are used in modeling elastomer layers and 2-D, 3-node, point-to-surface contact elements are used to model the contact between the composite and the metal fitting.

The orthotropic material properties used in the FEA analysis can be established using the rule of mixtures and laminated plate theory (LPT). To reduce FEA model size and processing time, grouping of composite layers with different materials and/or fiber orientations within a single model element layer can be applied. LPT is used to generate representative orthotropic material properties for grouped layers. The FEA models need to account for both material and geometric non-linearity.

The two common approaches to analysis of composites are the micromechanics approach and the macromechanics approach. The micromechanics approach is based on consideration of the elastic and thermal characteristics of individual laminas based on consideration of the interaction between the various constituents. The macromechanics approach, on the other hand, uses equations of orthotropic elasticity to calculate stresses, strains, and deflection, but assumes that composites have homogenous properties. After the determination of stresses in individual plies due to applied loads, acceptability of the design is based on comparing these values with the allowable strength of the material using a suitable failure criterion. For iso-

tropic materials that exhibit yielding, such as steel, the distortional energy theory (von Mises criterion) is commonly used. Since composites are neither isotropic nor exhibit gross yielding, several failure theories are being used to predict fiber failure under axial tensile or compressive stresses and predict matrix failures under transverse stresses and shear stresses (Salama, 1997). One simplification that is often used in engineering practice is to make the assumption that the composite is fully crazed as a result of the thermal stresses induced during cure. This represents a reasonably conservative assumption and allows simplification of the analysis because no attempt is made to monitor the progression of resin cracking. To account for the change in laminate behavior due to resin crazing, lamina properties are changing by reducing the transverse elastic properties as follows:

$$(E_{22})_{crazed} = 0.1 E_{22} (G_{12})_{crazed} = 0.9 G_{12}$$

 $(\mu_{12})_{crazed} = 0.001 \mu_{12} (\mu_{23})_{crazed} = 0.001 \mu_{23}$

ANALYSIS VALIDATION

Validating the accuracy of the analysis approach of composite risers is a critical part of accepting analysis as basis for design without the need to implement an extensive qualification testing program. Therefore, this objective was an important goal for the NIST-ATP Composite Production Riser (NIST CPR) Project. Figure 4 compares the mean failure envelope as predicted using previously described FEA analysis strategy with measured data on the 10% inch NIST CPR with trap-lock MCI joints. The comparison involves joints subjected to internal pressure, external pressure, axial load, and combinations of pressure and axial loads. The results clearly demonstrate the accuracy of the predictions and their level of conservatism.

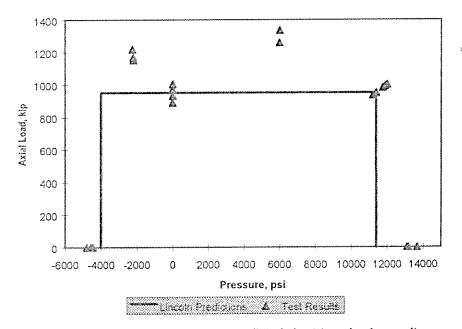


Figure 4. Comparison between predicted short-term load capacity of 10% inch NIST CPR joints and measured values

ALLOWABLE STRENGTHS FOR COMPOSITE MATERIALS

An important element of the design of the composite joints is the selection of appropriate allowable stresses for the different design

cases. These design cases include short-term loads, long term operating loads, and cyclic fatigue loads. Polymer-matrix composite materials exhibit creep rupture behavior, similar to the behavior of

some metals at elevated temperatures. Therefore, the safe design of structures using these materials requires the consideration of load durations, the probabilities of the loads occurring and the acceptable probabilities of failure. The approach that has been adopted for riser design is to establish long term performance of composite structures using the probability functions developed by Robinson (1991) for the stress rupture performance of composite pressure vessels. This approach degrades the static strength allowables based on load duration and acceptable probability of failure (P_t). To demonstrate the

validity of this approach, several NIST CPR joints were subjected to different levels of internal pressure with end effects (i.e., combined internal pressure and axial load). The joints were held under load until failure. The results of these tests are presented on Figure 5 along with static fatigue curves calculated using Robinson's method, with slope adjusted for a better fit to the data. The results demonstrate the validity of using Robinson's approach for predicting the stress rupture performance of filament wound composite risers.

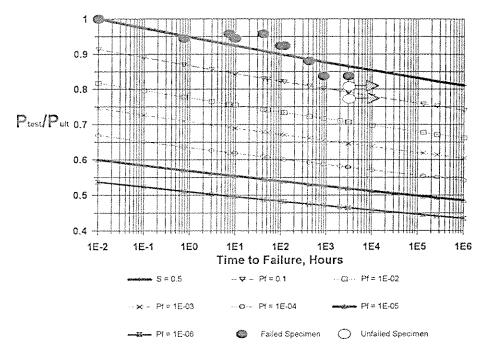


Figure 5. Composite Riser Stress Rupture Predictions Based on Evaluation of NIST CPR Static Fatigue Tests Using Robinson's Method.

There are two approaches that have been proposed for establishing allowable stresses for composite risers. The first approach is based on considering the B-Basis or A-Basis strength values for composite laminates as equivalent to the minimum tensile strength value used for metal components, and impose on this value the API RP 2T safety factors specified in Table 2 (API, 1997). The

B-basis strength is the strength value above which at least 90% of the test results are expected to fall, with a confidence of 95%. The A-basis strength is the strength value above which at least 99% of the test results are expected to fall, with a confidence of 95%. Table 3 provides an example of typical mean, B-basis and A-basis strength values for carbon fiber composites.

Table 2. API RP 2T Allowable Stress Limits for Risers

Design Parameter	Design Case			
_	Installation	Normal/operating	Normal/extreme	
Net Section Stress				
% yield strength	67	67	80	
% ultimate strength	50	50	60	
Local Bending Strength	***************************************			
% yield strength	87	87	120	
% ultimate strength	67	67	90	

Table 3. Typical Strength Properties of Carbon Fiber Composites

Property	Mean B-Basis Ksi (MPa) ksi (MPa		A-Basis ksi (MPa)
Room Temperature, we	ŧ		
Fiber Tension	407 (2806)	382 (2634)	366 (2524)
Fiber Compression	188 (1296)	175 (1207)	163 (1123)
Interlaminar Shear	13.4 (92)	12.4 (85)	11.7 (81)
170°F, wet			
Fiber Tension	361 (2490)	340 (2344)	325 (2241)
Fiber Compression	165 (1138)	153 (1055)	144 (993)
Interlaminar Shear	11.8 (81)	11 (76)	10.3 (71)

The second approach is to establish allowable strength values based on a probability of failure of 10⁻⁵ within the service life of the riser system. The probability of a riser joint failing under a given design case during a specified service life can be obtained by multiplying the probability of the composite joint failing during the expected duration of the loading by the probability of occurrence of a given load within the specified service life, as follows:

$$P_{f(T)} = P_{f(CDR)} \times P_L = 10^{-5}$$

where:

 $P_{f(T)}$ = Total probability of failure of a CDR joint under a given load during the service life;

P_{I(CDR)} = Probability of failure of a CDR joint during the expected duration of the given load;

 $P_L = Probability$ that the given load will occur during the service year service life.

The probability of failure of a riser joint at an application of a given load with a given duration, $P_{f(CDR)}$, is established as follows:

$$P_{f(CDR)} = 10^{-5} / P_L$$

Using this approach, it is necessary to assign values to P_L for the various design cases and the loading duration for each design case. The value of P_L can be calculated for an event that will occur once in R-year (return period) in a given service life (T, in years) based on the extreme analysis procedure as follows:

$$P_L = 1 - (1 - 1/R)^T$$

As an example, the value of P_L for a 100-year storm event and a service life of 25 years is 0.22. The required reliabilities are used with the creep rupture curves shown in Figure 5 to calculate allowable stress ratios for the composite material for each design case. Allowable stresses for each design case

are obtained by multiplying the mean material strength by the allowable stress ratio. These allowable stresses can be thought of as safe "working stress" levels that ensure that the product has the desired probability of surviving each design case. For both production and drilling riser studies, allowable strength values based on the reliability approach and values based on the API RP-2T safety factors and A-basis strength, were very similar.

Another critical element in the design of composite risers requires establishing a fatigue design curve to assess fatigue performance, particularly for the trap-lock MCI joints. Similar to metals, the fatigue design curve for composites can be presented in terms of a two parameter fatigue S-N curve that has the form NSⁿ=A. The first parameter is the slope (n) of the S-N curve. The slope of the fatigue curve depends on the material system (i.e., carbon or glass) and on the failure mode (i.e., tensile, compressive, or shear). For failure dominated by shear strength, as is the case for the traps, published data indicates that the value of n for carbon fiber composites is between 18.73 and 23.83 (Karayaka and Wang, 1999; Pipes, 1974; Awerbush and Hahn, 1981). To ensure conservatism, the lower value (18.73) is proposed. The second parameter (A) is derived by considering the static strength of the joints at the service temperature as the fatigue strength corresponding to 1/4 cycle. The accuracy of the static strength predictions has been confirmed as shown in Figure 3. For the mean fatigue curve, the value selected is the mean strength at temperature based on static ultimate test data (Table 2). For the design fatigue curve, the value used is the A-Basis allowable strength at temperature (Table 2) based on the statistical distribution of the static ultimate test data. Using the above approach, the mean S-N fatigue curves for 70°F and 170°F service are as shown in Figure 5, along with design curves based on A-Basis allowables. Shown also on Figure 5 are the results of fatigue tests on twelve NIST CPR joints at three different stress ranges. The accuracy of this approach is demonstrated by the test results.

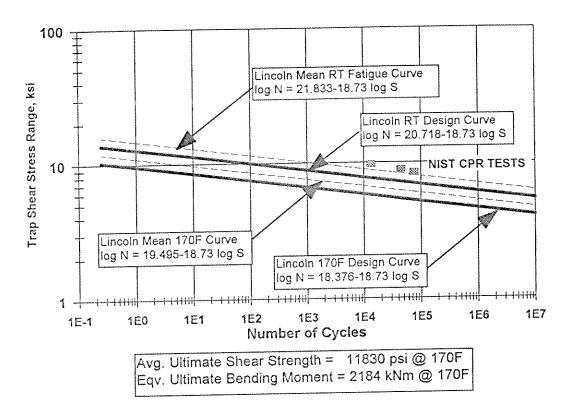


Figure 5. Comparison between Fatigue S-N curves for Traplock MCI's and test results using NIST CPR joints.

DAMAGE PROTECTION

Composite risers can be subjected to several damage mechanisms during their fabrication, installation, and service. These damage forms must be identified and addressed as part of the design strategy. Carbon fiber composite riser pipes will have sufficient resin erazing due to the thermal stresses induced by the curing cycle and the mechanical stresses induced during the shop pressure test. This crazing will result in a composite structure that does not provide sufficient fluid tightness under pressure. Therefore, carbon fiber composite risers must be provided with an internal elastomeric and/or metal liner to ensure fluid tightness. The internal liner must be compatible with the internal fluids. Depending on the application of the riser, production, workover, transport, water injection, or drilling, the liner will be in contact with one or more of these fluids: hydrocarbon, seawater, drilling muds, hydrochloric acid, biocides, chloride or calcium chloride, corrosion and scale inhibitors, methanol/glycol, and demulsifiers. Also, because of the resin crazing, the exterior of the composite riser must be provided with an external elastomeric liner in order to prevent migration of external seawater into the composite wall and through the MCI. For elastomeric liners, careful design consideration must be given to the sealing mechanism between the liners and the metal termination. For the NIST ATP production riser, a special pre-molded elastomeric lip seal was used to ensure that internal fluids would not migrate through the seal-termination interface. Several design and manufacturing iterations were necessary until acceptable design was established. The long-term performance of the latest seal design under high internal pressure (above 9000 psi) has been demonstrated. This experience shows that the mere bonding of an elastomeric liner to a pre-fabricated composite riser joint will not be sufficient to ensure long-term leak tightness because the longterm integrity of the adhesive bond line cannot be assured.

For drilling and workover risers, the internal liner will not only get in contact with chemicals, it will also be in contact with running tools such as drill bits, milling tools, fishing overshots, coring tools, under reamers, packers, safety valves, etc. The experience on using an internal abrasion and wear elastomeric (a 3-mm hydrogenated nitrile rubber (HNBR)) liner that is adhesively bonded to Heidrun's titanium drilling riser suggests that tear damage of the elastomeric liner by running tools is inevitable. Therefore, an elastomeric liner alone may not be sufficient to ensure pressure integrity because of the high probability of its tearing damage. In order to ensure leak tight conditions even if the internal elastomeric liner is damaged, a metal liner must be used. The use of metal liners offers an additional advantage because they can be welded to the MCI and therefore eliminate the concern of possible leak around the seal area. However, the use of metal liners complicates the design of the riser joint because of the thermal and stiffness mismatch between the metal and the composite pipe. Use of steel may be proven difficult because the risers are subjected to axial and bending loads, making it necessary to employ low stiffness metals such as titanium. Because of the poor wear and abrasion resistance of titanium, an elastomeric liner must also be incorporated, similar to the one used for Heidrun's titanium risers. If, however, it can be proven that a thick elastomeric liner or a reinforced liner will be able to withstand potential damage by the running tools, the use of metal liners can be avoided.

Another important damage mechanism that must be accounted for in design of composite risers is external damage from mishandling and impact by dropped objects. Resistance to damage due to mishandling and small dropped object impact can be provided by an external elastomeric liner and a fiberglass overwrap that is used to

compact the rubber liner during cure. A detailed failure mode, effect and criticality analysis (FMECA) on Heidrun TLP indicated significant probability of a riser joint being subject to falling object impact loads of about 50 kJ for joints located below the 50 m water depth and 250kJ for joints located above this water depth. A dropped object such as 13 5/8 inch easing joint induces this level of impact energy. Tests on a composite drilling riser joint that is designed for field testing on Heidrun showed that the 50 kJ criterion can be satisfied by the 0.090" (2.3 mm) external liner of HNBR and the 0.040" (1 mm) thickness of E-Glass/epoxy composite filament wound over the HNBR. However, for joints located above the 50 m water depth, a special impact protector is required. The system that has been proven satisfactory for Heidrun's composite riser has alternating plies of bidirectional woven fiberglass cloth and random oriented fiberglass mat and crushable foam material of epoxy macrospheres and glass microspheres embedded in a polymer matrix (Salama, et al. 1999).

Protection from fire is not considered a requirement for the composite riser joints because they are only proposed for use underwater.

MANUFACTURING AND QUALITY ASSURANCE

The manufacture of composite risers is performed using computer-controlled multi-axis filament winding machines. Prior to winding the composite, the internal liners (elastomer or metal) and the end fittings are accurately located and held in place by specialized tooling details at each end of the mandrel. To facilitate high-rate production, fiberglass and/or carbon rovings are impregnated with uncured epoxy resin during the winding process. The wind program controls all the layer sequence and wind angles, as well as the resin content and fiber tension.

The low-angle helical layers are wound over the end fittings and reversed through low-profile domes located outboard. After the completion of a helical layer, it is secured between the trap geometry and dome, and then cut loose from the dome. The helical layers are then compacted into the grooves in the fitting by winding structural fiber over it. Localized axial reinforcements are incorporated into the trap in a similar manner. Following winding, the mandrel-wound assembly is removed from the winding machine and placed into a rotating cure dolly in a cure oven. After cure and inspection, the assembly is placed again into the winding machine, where an external liner is spiral wrapped on the O.D. of the composite. A final overwrap of two layers of fiberglass is wound over the HNBR for compacting it and providing extra abrasion protection. After the overwrap, the part is placed back in the oven for the final cure. After cooldown, the mandrel is removed and the part is inspected. For risers, most of the load resistance is provided by carbon fibers. Circumferential layers of E-glass are sometimes used to increase the buckling resistance of the cross-section by increasing the separation distance between the inside and outside carbon circumferential reinforcements. Also, hybrid layers of carbon and E-glass fibers can be used to increase the damage tolerance and impact resistance of the tube wall.

Although many non-destructive testing (NDT) techniques have been successfully applied for inspection of composite components, the application of these techniques for inspecting composite risers can be limited because of the presence of internal and external elastomeric liners. Therefore, the overall integrity of the composite riser must heavily rely on the successful implementation of a comprehensive quality assurance program (QAP). The basic elements of a QAP include inspection and testing of all raw materials (fibers, resins, adhesives, etc.), detailed specification of all manufacturing parameters

(temperature, time, winding speed, winding tension, etc.), documentation of all specified process data, in-process inspection of manufacturing process, dimensional and visual inspection, proof load testing, and some destructive testing of fabricated components. Destructive testing is used not only to confirm design and manufacturing, but also to develop monitoring parameters such as stiffness, local displacement and acoustic emission signature that can be used to verify the quality of composite risers during proof load testing.

CONCLUSIONS

Solutions to the key technical challenges that are being faced by designers and fabricators of composite risers have been presented. These challenges include interface between the composite pipe and the metal connector, internal and external damage protection, analysis methods and their validation, allowable strength parameters, and manufacturing and quality control strategy. The validity of these solutions has been demonstrated by results on both composite production and drilling riser joints. The technical issue that has not been fully addressed is the extent of use of NDT techniques to validate the quality of composite risers.

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SI METRIC CONVERSION FACTORS

nsi x 6.894 757	E+00	= kP	a
ft x 3.048	E-01	= m	
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^{*} Conversion factor is exact.

Update: Rethinking deepwater tethers

ension leg platforms (TLPs) are buoyant platforms used for off-shore drilling and oil production. Unlike stationary platforms, which are used in shallow waters and have rigid, compression-loaded legs mounted into the sea floor, TLPs are vertically or near vertically moored with tethers that limit the heave motion of the platform. By limiting this vertical motion, TLPs are able to support wellhead on the platform itself, giving them a significant advantage over other floating structures.

The key element of the TLP is the vertical mooring system, which restrains both the vertical and lateral motions of a TLP hull. The mooring system consists of foundation and tether systems. The foundation is the means for transmitting the loads from the

tether into the seabed, and the tether system is the link between the seabed foundation and the buoyant hull.

By all accounts, future offshore oil exploration will tend toward deeper and deeper waters, and the tether is the part of the TLP system most affected by increasing ocean

depth. Current designs use steel pipe as the tether, but as water depth increases, the walls of these pipes must be substantially thickened in order to resist the increasing external waterpressure. This results in a significant weight increase that will cause the tether to sag as the buoyant hull moves laterally, reducing its ability to restore the platform to its original position. The sag also results in a loss of axial stiffness in the tether, which is critical to ensure that the natural periods of heave, roll and pitch motions are maintained below four seconds to avoid platform resonance.

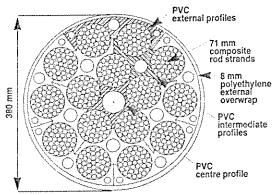
Two advanced composites solutions to this problem have been proposed: composite pipe and composite cable. Both solutions offer lower weight, higher strength and stiffness, superior corrosion resistance, and improved fatigue resistance over the steel pipe currently in use.

The approach that surpasses the existing steel paradigm and best utilizes the properties of advanced composites is the carbon fiber composite cable. It is being developed by Conoco Inc. (Ponca City, Okla.) and Kvaerner Oilfield Products (Oslo, Norway). The cable structure wholly avoids the factor of collapse resistance. Normally, the hollow tubes of steel tethers have dry interiors to reduce their weight when submerged. For composite tethers, the material density is low enough so that submerged weight is a negligible factor.

The first step in the manufacture of the cable is to pultrude small-diameter (1/8- to 3/16-inch) composite rods. The fibers used are AKZO Fortifil 556 80K tow and Zoltek Panex 53. Customized epoxy resins are used as the matrix.

Strands are then manufactured from 100 to 300 rods using a typical wire rope stranding process. The use of a light

Comparative Cost Ratio:	Steel Pine	Composite Cable
Design and Engineering	10.0	10.0
Tether Body Materials	12.5	21.6
Tether Equipment	35.2	20.9
Site and Equipment Preparation	3.2	2.8
Tether Fabrication	13.4	6.4
Installation	47.1	26.6
TOTAL * * * *	121,4	88.3



fillustration of cross-section tether.

helical twist, typically 2-3° on the outer rods, with a polyethylene overwrap, gives sufficient coherence to the strand for handling, coiling and transportation without significantly affecting the axial strength and stiffness. The strands are cut to depth length and wound on a spool for further handling.

The strands are then assembled into a tether using a wire rope manufacturing facility or using an umbilical fabrication facility. Using the umbilical approach, the tether cross-section can be constructed from a number of composite rod strands, each located in a separate channel created by plastic profiles. The profiles are made of polyvinylchloride and are extruded into shape and combined with the carbon fiber/epoxy strands in one process. Because there is no bond between the PVC profile and the strands, the strands are free to move individually along the length of the tether, allowing them to adjust to and better distribute loads along the cable.

The last step in creating a composite cable is the "termination process," which secures the tether to a metal fitting. This is accomplished by potting the tether in a conical steel termination fixture using a metal-filled epoxy resin. Since the design concept is mainly driven by the stiffness of

the tether, a high-load-transferring termination is not required.

As an extra benefit, an optical fiber network can be placed within the composite cable to monitor its structural integrity. By embedding optical fiber in this manner, it is possible to measure strain and failures in each rod and strand. The exact

position of failure can be relayed, and measures can be taken to correct such problems as they occur.

A sample cost-comparison between steel pipe and composite cable is shown for a 40,000-ton steel platform in 4,500 ft of water (the data is shown as a ratio between the two systems rather than actual dollars and includes those items which may be different between the two systems). This data is based on the use of Zoltek or Akzo PAN 33 Msi modulus large tow fibers, which are presently available at \$8-9/lb.

The concept is cost-effective when compared to steel cables, and could open a very large market for carbon fiber. The TLP used in the cost study, for example, would require over 1.5 million lbs. of carbon fiber. A market of that size would certainly help to drive down the price of large-tow carbon fibers. **IRCC**

Questions about this concept can be directed to Mamdouh M. Salama, Conoco, Inc. E-mail mdouh.m.salama@usa.conoco.com



COMPOSITE MATERIALS FOR OFFSHORE OPERATIONS - 2

High Pressure Composite Accumulator Bottles

Donald Baldwin¹, Norman Newhouse¹, and K. Him Lo²

REFERENCE: D. Baldwin, N. Newhouse, and K. H. Lo, "High Pressure Composite Accumulator Bottles," *Composite Materials for Offshore Operations* – 2, S. S. Wang, J. G. Williams, and K. H. Lo, Eds., American Bureau of Shipping, 1999, pp. 293-305.

ABSTRACT

Composite Accumulator Bottles (CAB's) are being produced for the offshore oil industry by Lincoln Composites of Lincoln, Nebraska. CAB pressure vessels are all-composite pressure vessels, based on technology developed by Lincoln Composites for the Natural Gas Vehicle (NGV) market. There are three CAB designs currently qualified to the requirements of ASME Section X. The materials of construction, manufacture and testing of the pressure vessels are discussed. The development of larger vessels is planned to meet the needs of the offshore industry.

INTRODUCTION

Lincoln Composites, formerly Brunswick Composites, is currently producing all-composite pressure vessels for the offshore oil industry. These pressure vessels are the first application of composite materials in primary structural systems in the offshore industry. To date, vessels have been developed for Shell's Mars, Ram Powell and Ursa Tension Leg Platform (TLP) riser tensioning systems. These vessels are certified to the ASME Boiler and Pressure Vessel Code, Section X, Fiber-Reinforced Plastic Pressure Vessels. Even with the conservative design margins required for certification under Section X, Lincoln Composites' Composite Accumulator Bottles (CAB's) offer significant weight savings relative to steel bottles without the increased costs usually associated with composite materials.

LINCOLN COMPOSITES AND COMPOSITE PRESSURE VESSELS

Lincoln Composites, formerly Brunswick Composites, has been involved in composite filament winding since the 1950's. The first composite cylinders were manufactured with

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an elastomeric liner and a fiberglass/epoxy overwrap, and were primarily for use on military aircraft. As technology advanced, the need for lower permeation rates and lighter weights resulted in the development and use of composite cylinders with metallic liners and overwraps constructed of aramid and carbon fibers. These composite cylinders were and still are used in many military and civilian aircraft, missiles, flotation systems and space applications.

In 1991, Lincoln Composites initiated a program to develop an all-composite fuel tank for the Natural Gas Vehicle (NGV) market. Figure 1 is a representative cross-section of an all-composite pressure vessel. The term "all-composite" refers to a vessel with a non-loadsharing liner made of plastic. Plastic liners have low permeation rates and a virtually unlimited fatigue life. They are also less expensive and require shorter lead time for procurement than metal liners. The first all-composite fuel tank was certified in June 1993 to the American National Standard (ANSI) AGA NGV2, Basic Requirements for Compressed Natural Gas Vehicle (NGV) Fuel Containers [1]. Since 1993, Lincoln Composites has designed, developed and certified over thirty (30) NGV tank configurations.

The CAB family of pressure vessels is an extension of the all-composite pressure vessel technology developed for NGV application. They have been developed primarily for use as energy accumulators on riser tensioning systems. To date, three configurations have been qualified per ASME Section X, for application on the Mars, Ram-Powell and Ursa TLP's (see Figure 12). Inquiries have been received from parties interested in using CAB's for other offshore applications, some of which would require vessels much larger than the currently qualified configurations.

ALL-COMPOSITE PRESSURE VESSELS

Materials of Construction

As shown in Figure 1, the all-composite pressure vessels produced by Lincoln Composites consist of a hybrid composite shell, combining carbon and fiberglass reinforcements impregnated with epoxy resin, filament wound over a High-Density Polyethylene (HDPE) liner. The carbon and E-glass fibers are combined at the ply level, with both fiber types in the filament winding band. As the product line is expanded to include larger diameter vessels and thicker walls, the wall thickness will likely consist of carbon/epoxy structural layers with a sacrificial overwrap of fiberglass for damage mitigation. These combinations of carbon and fiberglass reinforcement provide a means of bringing together the best attributes of both materials. HDPE is an excellent performer as a liner material. Though inexpensive, it is easily formed and has very low permeation rates.

Carbon fiber is known for its excellent fatigue performance. At a safety factor of 5.0, it has a projected reliability of 0.999999 for a lifetime in excess of 10,000 years [2], and a cyclic fatigue life in excess of 10¹² cycles [3]. There is some concern about the damage

tolerance of carbon fibers. This is due in part to the high elastic modulus of carbon, its crystalline nature, and the fact that due to its high strength, carbon pressure vessels typically have thinner walls relative to glass-reinforced vessels.

The incorporation of E-glass fiber into the design addresses the above concerns about damage tolerance. E-glass provides improved damage tolerance by itself, but more importantly, it increases the wall thickness of the laminate. By increasing the wall thickness, the effect of damage to a vessel's outer layers is lessened because the ratio of damaged layers to undamaged layers is decreased. Also, increased wall thickness increases the stability of the vessel's cross-section, reducing its susceptibility to localized buckling or "oil-canning". The use of E-glass to improve damage tolerance is very cost effective compared with simply adding more carbon fiber to the wall. As vessel wall thickness increases with increasing diameters and burst pressure requirements, equivalent damage tolerance can be achieved with less E-glass content. Very large vessels may be reinforced with just carbon fiber to minimize weight and still exhibit adequate damage tolerance. A full overwrap of fiberglass is recommended to attenuate and distribute impact loadings, and to provide a sacrificial layer to withstand cuts, scrapes and gouges.

Reinforcing fibers are encapsulated in a polymeric matrix, usually a thermosetting resin system such as epoxy. Lincoln Composites' LRF-R0600 is a proprietary epoxy formulation with low cure temperature and time, excellent environmental resistance, and high compatibility with carbon and glass fibers. It is used for all ASME pressure vessel and NGV fuel tank applications and is qualified to ANSI/AGA NGV2 requirements.

The liner is comprised of two injection molded HDPE domes fusion welded to an extruded HDPE tube. HDPE is inexpensive, has good environmental resistance, is easily formed, and has low permeability. Based on measured permeation rates, a vessel with an HDPE liner that was pressurized to 3600 psi with air would lose only about 0.01 psi per year. HDPE has been used for over 30 years in natural gas pipelines, and is used for containers to store various hydrocarbons.

Pressure Vessel Design for ASME Section X Qualification

The CAB's currently being produced by Lincoln Composites have been designed to meet or exceed the requirements of the ASME Boiler and Pressure Vessel Code, Section X, Fiber-Reinforced Plastic Pressure Vessels. The design pressure of these vessels is 3000 psi, which is the maximum design pressure allowed by Section X for filament wound vessels with uncut filaments. The design temperature range is -20°F to 150°F. Section X and requires that the vessel be cycled from atmospheric pressure to design pressure: a total of 33,000 times, with 3000 cycles at -20°F and 30,000 cycles at 150°F, prior to a burst test at 150°F. For filament wound vessels with uncut filaments, the burst pressure after cycling must exceed five times the design pressure, in this case 15,000 psi. Lincoln Composites designs these vessels for a minimum virgin burst pressure of 16,500 psi

(110% of the minimum requirement), to account for variability in fiber strength and the manufacturing process.

The high burst pressures required for ASME Section X qualification result in vessel walls which are approximately twice as thick as required for an NGV vessel of the same diameter. Therefore, the vessel designer must not only ensure that sufficient reinforcement is provided, but must also consider the problems involved in manufacturing such thick-walled vessels. More than 50 filament wound layers may be required to create a typical CAB cylinder wall. The placement of the reinforcing fiber is critical to vessel performance, in particular the location of the pattern turn-arounds or reversals at the end of each circuit of application. For example, a CAB design may have as many as six different angles of axial reinforcement to avoid an excessive buildup of fiber around the polar bosses. Traditional pressure vessel design methods such as netting analysis and laminated plate theory are useful in initial sizing of the vessel wall. However, to ensure producibility and to account for localized stresses, modelling tools which account for the variation in layer thickness when a layer is reversed in the vessel cylinder or on the vessel dome are required. Lincoln Composites has developed internal design codes for this purpose. An example of a wall cross-section resulting from these codes is shown in Figure 2.

Extensive use is made of Finite Element Analysis (FEA) to evaluate the pressure vessel design. As a minimum, a two-dimensional axisymmetric model of the vessel is constructed, with considerable effort going toward the accurate representation of as-built geometries and material properties. The FEA provides the best predictions available for the layer-by-layer stress condition of the vessel wall, particularly in the vessel dome and in the transition region between dome and cylinder. These results are post-processed using codes developed by Lincoln Composites to produce fiber stress plots as shown in Figure 3. The polar boss geometries are included in the FEA, for purposes of evaluating their working stress levels against code requirements.

The demonstrated safety factor of greater than 5:1 for the carbon-reinforced CAB's is sufficiently high that it has a virtually unlimited lifetime, in terms of both static and cyclic fatigue loadings. The Factor-of-Safety requirements of several industry standards for composite pressure vessels are listed in Table 1. The differences in safety factors between the various fiber reinforcements requires an understanding of their stress rupture behavior. The stress rupture characteristics of carbon are substantially better than those of glass. For example, if glass fiber is held at 80 percent of its average ultimate strength, its characteristic lifetime is about 1 hour, while carbon fiber held at 80 percent of its average ultimate strength would have a characteristic lifetime of over 1 million years. ASME Section X was developed more than 20 years ago for glass fiber reinforced pressure vessels and does not differentiate between fiber materials when assigning safety factors. This is considered very conservative for the CAB application, particularly for hybrid vessels. However, to satisfy regulatory requirements, a new standard incorporating lower safety factors and perhaps damage tolerance testing would need to be developed and approved.

Fabrication

The fabrication of an all-composite pressure vessel begins with the machining of the polar bosses. Numerically controlled machine centers are used to ensure repeatability and dimensional control (Figure 4). The bosses are located on the axis of the vessel and usually contain ports, although sometimes one end of a vessel is provided with a blank boss. The bosses for NGV use are usually machined from aluminum bar or impact forgings. For offshore application, 316L stainless steel is used because of its superior corrosion resistance.

The domed ends of the HDPE liner are injection molded around the vessel bosses as shown in Figure 5. The boss is retained in the dome using a mechanical interlock as shown in Figure 1. Keyways are cut in the top and bottom surfaces of the boss flange. The HDPE flows into these keyways during the injection molding of the dome. Bonding of the boss to the liner material is not required to maintain a gas-tight seal. Lincoln Composites has been granted a patent for this liner-to-boss joint.

A liner assembly consists of two injection-molded domes welded to a center cylinder section. The cylindrical portion of the liner is manufactured via a pipe extrusion process to produce a tightly controlled diameter and wall thickness. The process is similar to that used to produce plastic pipe for gas transmission.

The welding of the liner is also based on methods used to join lengths of HDPE pipe. A dome is placed in a weld fixture with a section of pipe that has been trimmed to length. The surfaces to be welded are then machined in an automatic facing operation to ensure that the weld faces are parallel and clean. After verification of alignment, a programmed weld sequence is initiated to complete the weld process. A heated platen is positioned between the dome and pipe for a controlled period of time and pressure. At the conclusion of a pre-set heating time, the platen is removed and the melted surfaces are fused by forcing them together for a controlled period of time (Figure 6).

Upon removal of the liner from the weld fixture, the external weld bead is removed and the fusion process is then repeated a second time for the other end of the liner. After completion of the second weld, the liner is dimensionally inspected for overall length and weld mismatch. The liner is then thermally treated to reduce any stresses induced by the weld process, and then re-inspected for overall length.

Filament winding of the composite laminate is accomplished in a computer-controlled multi-axis winding machine (Figure 7). To facilitate high-rate production, the fiberglass and carbon rovings are impregnated with resin during the winding process. The method of impregnation is proprietary to Lincoln Composites, and controls the resin percentage within 2% by weight. Fiber tension is pre-set and controlled during the wind process. The layer sequence and wind angles, as well as the resin content and fiber tension, are all controlled by the wind program.

After completion of the filament winding process, the vessel is heated using infrared heaters until the surface is tack-free. This "b-stage" solidifies the resin matrix but does not result in complete polymer crosslinking. The vessel is then moved to a curing oven where it is heated until the epoxy matrix is completely crosslinked. At this point, the fabrication of the vessel is complete except for coating/painting,. NGV vessels are painted after the b-stage to promote adhesion. However, ASME Section X requires that proof testing be performed on unpainted vessels, so any desired coating systems are applied to the vessel after acceptance testing. Typically, this would consist of a low IR epoxy polyamide primer and a polyurethane barrier or top coat.

Qualification Testing for ASME Section X

Upon completion of the pressure vessel design, a Design Verification Test (DVT) unit is fabricated and burst at room temperature. This test is not required by ASME Section X, but is conducted to evaluate vessel performance prior to proceeding to cycle testing. Fabrication of a DVT unit also provides an opportunity to develop manufacturing processes (i.e., "work out the kinks"). A minimum burst pressure of 16,500 psig (110% of the minimum burst-after-cycle pressure of 15,000 psig) for a virgin vessel tested at room temperature is considered sufficient margin to proceed to cycle testing.

After a successful DVT burst, the ASME qualification unit is fabricated. The design pressure of these vessels is 3000 psi, the maximum design pressure allowed by Section X for filament wound vessels with uncut filaments. The design temperature range is -20°F to 150°F. Section X requires therefore that the vessel be cycled from atmospheric pressure to design pressure a total of 33,000 times, with 3000 cycles at -20°F and 30,000 cycles at 150°F, prior to a burst test at 150°F. For filament wound vessels with uncut filaments, the burst pressure after cycling must exceed five times the design pressure, in this case 15,000 psi.

Acceptance Testing of Production Units

Each CAB production unit is subjected to a series of acceptance tests to verify liner and composite integrity (Figure 10). This test sequence includes a proof pressure test, weight and internal volume calculation, hydrostatic leak test and a final dimensional inspection.

The first step in the process is to determine tank weight and volume. This is done by weighing an empty tank and then weighing the tank after it is filled with water. The tank is then subjected to three (3) hydrostatic pressure cycles. Per ASME Section X, the first cycle is performed at 4500 psig, 1.5 times the design pressure. This satisfies the hydrostatic test requirement for production units. Any air that is entrapped between the liner and composite overwrap is removed by this cycle.

For the second pressure cycle, the tank is pressurized at a rate of 200 psig per second and held at the design pressure of 3000 psig for a minimum of 30 seconds. Volumetric

expansion is measured during this pressure cycle, and the permanent set and elastic expansion are calculated.

The third pressure cycle is a leak test. The tank is again pressurized at a rate of 200 psig per second, and is held at design pressure of 3000 psig while the tank is carefully examined for leakage.

PRESSURE VESSELS FOR OFFSHORE APPLICATIONS

Lincoln Composites currently has three CAB designs qualified to the requirements of ASME Section X. These vessels are being fielded on the Mars, Ram Powell and Ursa TLP's. Lincoln Composites' CAB's weigh about one-fourth to one-third as much as an equivalent steel vessel, yet are priced competitively. Dimensional, volumetric and weight data for Lincoln Composites' family of CAB pressure vessels are listed in Table 2.

Figure 11 shows the installation of a Mars riser tensioning system with CAB's mounted on the tensioners. These 50-gallon, 365-pound vessels were qualified in late 1995, and over 120 units are currently in service in the Gulf of Mexico. Their deployment was significant as it was the first use of composite materials in a primary structural system offshore. The second CAB design was qualified to ASME Section X in late 1996. This 65-gallon, 485 pound vessel was designed for the Ram Powell and Marlin TLP riser tensioning systems. A third CAB configuration has been designed for the Ursa TLP riser tensioning system. This 85-gallon vessel is 104 inches long and weighs 565 pounds.

The three currently qualified CAB design are shown in Figure 12. Designs have been developed for 40-inch O.D. and 46.7-inch O.D. CAB's for accumulator and air pressure vessel applications. It is anticipated that at least one of these larger designs will be qualified sometime in 1998.

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Table 1-Fiber Factors of Safety				
Standard	Glass	Aramid	Carbon	
Aerospace	3.0 - 4.0	1.5 - 3.0	1.5 - 2.0	
FRP-1	3.33	3.33	NA	
FRP-3	3.5	3.0	2.25	
NGV2 / FMVSS 304	3.5	3.0	2.25	
ASME	5.0	5.0	5.0	

Table 2-Lincoln Composites CAB Data Summary				
Diameter, in	Length, in	Volume, gal	Weight, lb	Burst-After-Cycle, psig
173	82.5	50	365	16,391
20.1	81.7	65	485	17,040
199	104	85	565	18,600

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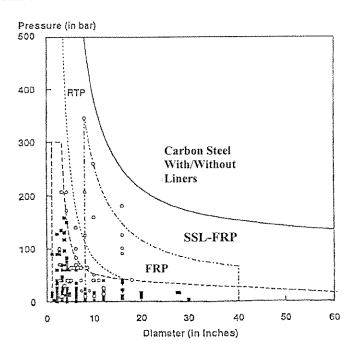


Figure 1. - Operating envelopes of carbon steel, FRP, lined carbon steel pipe, Steel Strip Laminate (SSL-FRP) and Reinforced Thermoplastic Pipe (RTP) pipe systems ¹⁶. (Filled squares - GRE; Open Circles - Lined Carbon Steel)

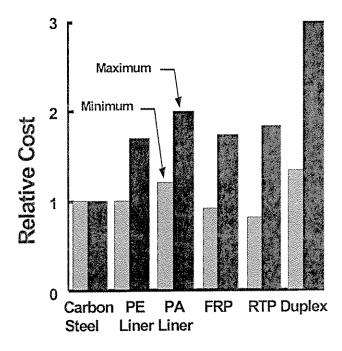


Figure 2. – Installed (CAPEX) costs of pipe relative to carbon steel. 16

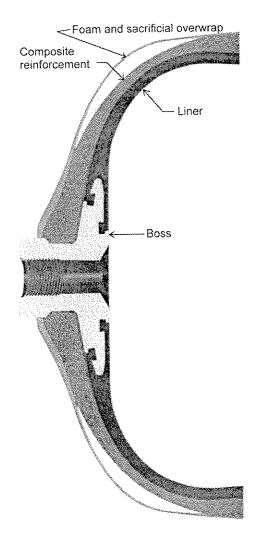


Figure 1. The Lincoln Composites all-composite pressure vessel consists of an HDPE liner with integral port bosses (U.S. Patent #5,427,845) and a hybrid composite overwrap. To provide impact protection in NGV applications the vessel domes are encapsulated in rigid foam (U.S. Patent 5,476,189) and the vessel is over-wrapped with non-structural layers of fiberglass. This has not been required in CAB applications because of the thicker vessel walls required for ASME Section X qualification.

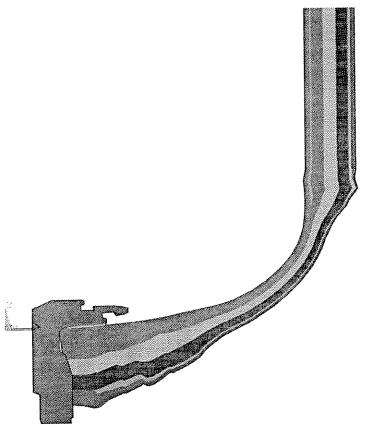


Figure 2. Lincoln Composites uses internally-generated codes to predict laminate buildups during the design of thick-walled pressure vessels.

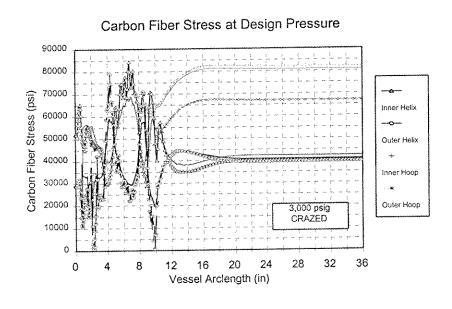


Figure 3. FEA results are post-processed to produce fiber stress predictions. This information is combined with testing to develop design allowables.

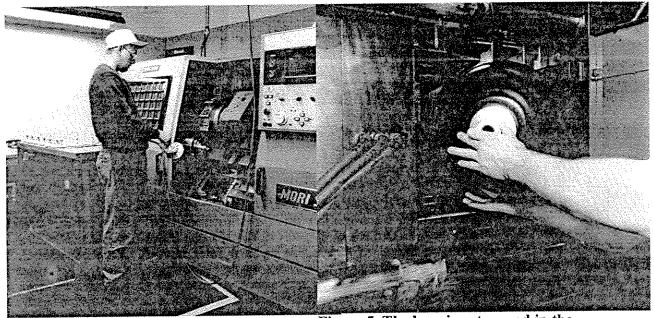


Figure 4. Stainless steel CAB bosses being machined in a numerically-controlled lathe.

Figure 5. The boss is entrapped in the HDPE dome during the injection molding process.

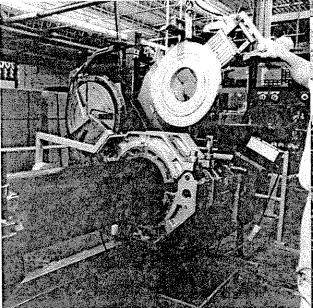


Figure 6. The injection molded domes are fusion welded to extruded tubing to form the vessel liner.



Figure 7. Epoxy-impregnated strands of carbon and E-glass fiber are filament wound over the liner.

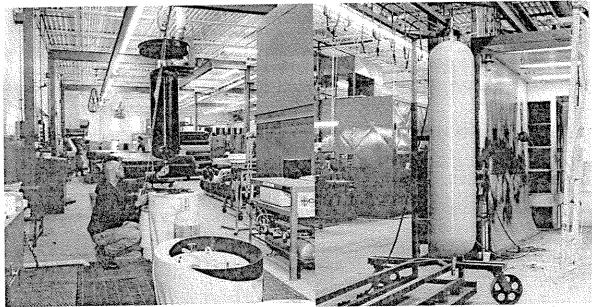
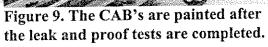


Figure 8. Every vessel is leak- and proof-tested prior to shipment.



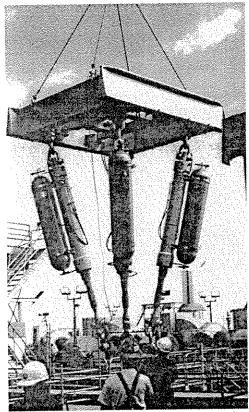


Figure 10. CAB's installed on a riser tensioning system.

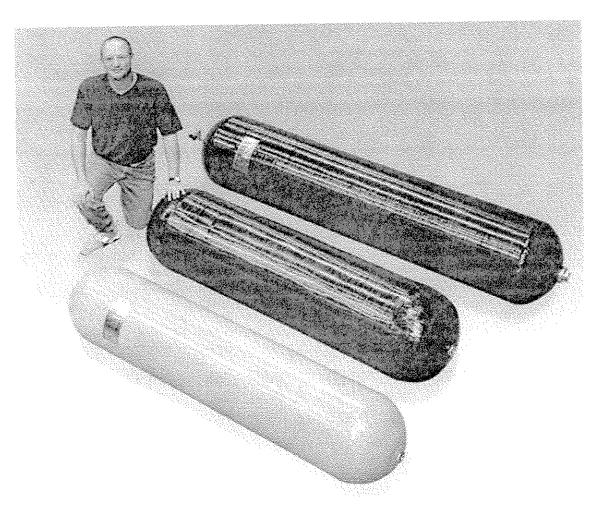


Figure 11. Lincoln Composites currently has three CAB designs qualified to ASME Section X.



OTC 10912

Advanced Design Methodology for Synthetic Moorings

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ABSTRACT

Synthetic mooring ropes are among the several alternatives being developed for positioning deepwater floating platforms. These ropes are constructed from polymer fibers such as polyester, nylon, or aramid. Individual fibers are grouped in yarns and strands, and overlayed to yield ropes of different diameters. Synthetic mooring lines have shown to provide numerous advantages over steel cables, enabling deepwater exploration and production. Widespread utilization, however, entails addressing technical challenges in rope material characterization, dynamic response and mooring system design, installation, design life prediction, and reliability assessment.

In this paper, a polymer mechanics based methodology is presented to address the long-term performance of mooring lines. The methodology provides an insight into the time-temperature dependent nature of synthetic rope deformation. A procedure for estimating damage evolution and the residual strength of a synthetic mooring line is also discussed. Failure of mooring terminations is beyond the scope of this study. However, outlined deformation and failure models can be used to design terminations, which are subjected to localized multiaxial stresses.

INTRODUCTION

In addition to obvious weight savings, characteristics such as neutral buoyancy, lower pretension requirements, improved fatigue performance, and better corrosion resistance make synthetic ropes an attractive replacement for steel cables as mooring lines for deepwater floating vessels. The potential advantages of polyester mooring lines have been successfully demonstrated in several feasibility studies [1,2] and pilot [3,4] projects. These projects clearly illustrate the operational and

economic benefits of synthetic moorings and outlined the following technical challenges: (a) special requirements during installation, (b) complex loading history and associated time-dependent deformation during service, (c) a multitude of long-term failure mechanisms due to combined creep and fatigue, and (d) potential strength degradation, in part, due to hysteresis effects, seawater exposure, and fiber abrasion. These challenges may be overcome with long-term testing and physical deformation and failure prediction model developments, and further field demonstration projects.

In this paper, a polymeric mechanics based method is outlined to address deformation and failure of synthetic moorings. First, a review of mechanical characterization models of synthetic ropes is presented. Subsequently, a deformation model for synthetic moorings is described. Failure prediction methodologies for synthetic mooring ropes subjected to a marine environment are then discussed.

LITERATURE REVIEW

Single Fibers, Yarns, and Small Ropes

A number of studies [5-12] have been reported in the open literature on mechanical properties of synthetic fibers, yarns, and small ropes. Cyclic and creep fatigue data were obtained [6,7] for Nylon 66 and single polyester fibers, yarns and ropes in air and sea water for load frequencies ranging from 0.1 Hz (typical in a marine environment) to 20 Hz. It was observed that the strain at failure under different loading (monotonic loading, static fatigue and cyclic fatigue) is the same (Fig. 1). It was postulated that the failure mode of fibers was mainly creep rupture, regardless of the loading cases. Using the cumulative time under load as a failure parameter, creep rupture models for fibers may predict the failure in cyclic tests at different frequencies in wet and dry conditions. The fatigue resistance of Nylon 66 and single polyester fibers, yarns, and small ropes are of similar nature at all frequencies, when the S-N curves are plotted in the S-time to failure domain. Cyclic fatigue experiments [8,9] on small polyester ropes indicate that in a loading range up to 80% of the rope breaking strength, the accumulated fatigue and short-term rupture strains are comparable.

An experimental study to investigate the heat build-up in polyester filaments and yarns is discussed in [12]. In a single filament subjected to cyclic loading, the heat-build up due to hysteresis increased with strain amplitude. Comparisons of

heat build-up in yarns and ropes revealed that for lower strain amplitudes (of practical interest for mooring systems) only the material-related hysteresis occurred vis-a-vis friction between filaments and yarns. In extreme loading conditions, a temporary temperature increase is likely to occur due to both fiber-to-fiber abrasion and material hysterisis.

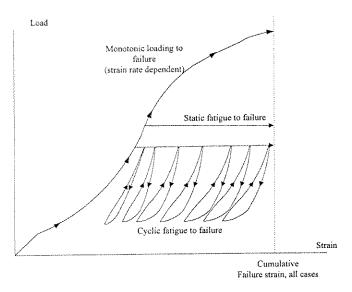


Figure 1. Schematic of deformation characteristics of synthetic fibers and ropes under monotonic, static fatigue, and cyclic fatigue loading [10].

Medium and Large Diameter Ropes

In addition to the material characteristics of their constituent fibers, the behavior of medium and large diameter ropes is also influenced by their construction. Consequently, the performance of large diameter synthetic ropes depends on a multitude of deformation mechanisms, including cumulative creep to rupture, hysteritic heating due to cyclic loading of filaments, friction and relative displacement between the yarns and strands.

Due to their larger cross-sectional geometry, the hysteresis and friction cause a temperature gradient with a higher temperature in the core of the ropes and a lower temperature at their surface. The core temperature has been observed [9] to reach an equilibrium value after several cycles of loading and is a function of the strain amplitude. A temperature gradient of 20 C is reported in a 0.5" diameter rope, which is significant as compared to the glass transition temperature of the synthetic ropes.

Figure 2 illustrates levels of details effecting deformation and failure characteristics of large diameter ropes. Two levels of additional challenge in describing the rope deformation behavior are: (1) establish the micromechanics relationship between the global yarn deformation and the individual fiber behavior (Yarn Mechanics), and (2) the relationship between the global rope deformation and the yarns (Rope Mechanics). Development of a rigorous model is beyond the scope of this tudy; rather, a methodology suitable for mooring analysis is

outlined.

As indicated in Figure 2, the fibers and yarn in a large rope are subjected to complicated loads, even the rope is in simple tension. Depending on the factors such as fiber size, rope size and structure, fiber location within the rope, each fiber sustain different transverse and shear loads in the fibers and yarns. This complexity leads to scale difference, which bring about the importance of development of physically based deformation and failure models with proper rope architecture.

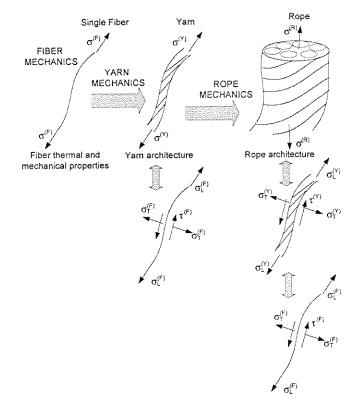


Figure 2. Global and local loads in fibers, yarns, and ropes.

POLYMER MECHANICS OF SYNTHETIC ROPE DEFORMATION AND DAMAGE

The displacement of a synthetic mooring line consists of mechanical and kinematic components:

$$\delta_{\text{Total}} = \delta_{\text{Mech}} + \delta_{\text{Kinematic}} \tag{1}$$

The kinematic displacement component is due to rigid body rotations and does not induce loads on the fibers. Largest kinematic displacement occurs during installation; however, some portion of the rope deformation is always kinematic during normal service conditions.

The mechanical displacement component is responsible for inducing loads on the fibers. The mechanical strain in a polymer fiber consists of various components:

$$\varepsilon_{\text{Mech}}(t) = \varepsilon_{\text{Eias}} + \varepsilon_{\text{T}}(t) + \varepsilon_{\text{V}}(t) + \varepsilon_{\text{D}}(t)$$
 (2)

the instantaneous elastic deformation, ϵ_{Elas} , is dependent on initial compliance and loading as follows:

$$\varepsilon_{\mathsf{Elas}} = \sigma_0 \, \mathsf{J}_0 \tag{3}$$

The thermal strain, ϵ_T , is induced by temperature change due to, for example, hysterisis heating of the rope:

$$\varepsilon_{T}(t) = \alpha \left[T(t) - T_{0} \right] \tag{4}$$

with α being the thermal expansion coefficient and T_0 is a reference temperature.

The term $\varepsilon_V(t)$ is the time-temperature dependent viscoelastic (or visco-plastic) strain in the polymer fiber. Under a constant load, the fibers exhibit a creep strain in the following form:

$$\varepsilon_{V}(t) = J(t-\tau) \sigma(\tau) \tag{5}$$

where J(t) is the creep compliance of the polymer fiber and $\sigma(\tau)$ is the fiber stress experienced at time τ . In the case of nonlinear viscoelastic deformation of a polymer fiber, the $J(t-\tau)$ in Equation 5 will be placed by a nonlinear creep compliance function $J(t-\tau; \sigma(\tau))$, which depends on the loading $\sigma(\tau)$ applied at time τ . The creep compliance functions J(t) or $J(t,\sigma(\tau))$ can be determined by standard dynamic-mechanical analyzer (DMA) or creep tests under mechanical loading.

The term ϵ_D (t) is the fiber strain induced by damage in the rope during service. The damage is caused by broken fibers, and friction and wear among individual fibers in a yarn and among yarns in a synthetic rope. In the context of micromechanics and the principle of strain equivalence in damage mechanics, the ϵ_D (t) may be expressed in the following form:

$$\varepsilon_{D}(t) = \frac{\sigma(\tau)}{1 - D(\tau)} J(t - \tau)$$
 (6)

where D is the damage in the rope under the nominal fiber stress $\sigma(\tau)$. The D(τ) can be quantitatively determined by considering the microstructure of a rope and the packing details of yarns in the rope.

A typical load history of a mooring line during its design life is schematically illustrated in Fig. 3. To determine the creep component of the rope fiber deformation under a variable external loading, the creep deformation can be expressed by

$$\varepsilon_{V}(t) = \int_{0}^{t} J(t-\tau) \frac{d\sigma(\tau)}{d\tau} d\tau$$
 (7)

Equation 7 needs to be integrated from the beginning of installation to the end of design life.

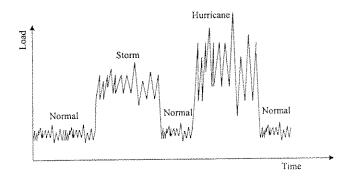


Figure 3. Typical load history of a mooring line.

INTERACTION BETWEEN FATIGUE AND CREEP DAMAGE AND LIFE PREDICTION

For synthetic fiber ropes, both creep and fatigue failure mechanisms operate simultaneously to govern failure. The incremental damage law can be written as follows:

$$dD \cong dD_C + dD_F + O(D^2)$$
(8)

where dD_C is damage due to creep, dD_F is damage due to fatigue, $O(D^2)$ is higher order damage term. This equation can also be written as:

$$dD \cong f_C(\sigma, T, (D_C + D_F),..)dt + f_F(\sigma, T, (D_C + D_F),..)dN$$
 (9)

where f_C and f_F are damage functions in fibers due to simultaneous presence of creep and damage.

Linear Damage Accumulation and Failure

In the case of linear damage accumulation, Equation 9 can be simplified as follows:

$$dD = \frac{dt}{t_{c}(\sigma, T)} + \frac{dN}{N_{F}(\Delta \varepsilon, T)}$$
(10)

where $t_c(\sigma,t)$ is the time to rupture in creep under fiber stress $\sigma(t)$ and temperature T, and N_F is the number of cycles to failure in pure fatigue under cyclic strain range $\Delta\epsilon$.

The total number of cycle to failure under combined fatigue-creep interaction is found by integration;

$$\int_{0}^{1} dD = \int_{0}^{N_{R}} \left[\int_{0}^{\Delta t} \frac{dt}{t_{c}(\sigma, T)} + \frac{dN}{N_{F}(\Delta \epsilon, T)} \right]$$
(11)

0

$$\frac{1}{N_R} = \int_0^{\Delta t} \frac{dt}{t_c(\sigma, T)} + \frac{1}{N_F(\Delta \varepsilon, T)}$$
 (12)

where Δt is the period of a fatigue cycle.

Nonlinear Damage Accumulation

It is well understood the presence of creep damage accelerates the growth of fatigue cracks and the presence of fatigue cracks increases the rate of creep damage. Using the damage evolution law of the power form;

$$\overset{\bullet}{\mathbf{D}} = \left(\frac{\sigma}{\mathbf{A}}\right)^{\mathbf{r}} (1 - \mathbf{D})^{-\mathbf{k}} \tag{13}$$

where A, k, and r are creep damage coefficients for the polymer material determined from pure creep tests, one may use the nonlinear damage accumulation model by Rabotnov and construct a general evolution law under conditions of creep-fatigue interaction as

$$\int_{0}^{1} dD = \int_{0}^{N_{R}} \left(\frac{\sigma}{A}\right)^{r} (1-D)^{-k} dt + \left[1 - (1-D)^{\beta+1}\right]^{\alpha} \left[\frac{\sigma_{max} - \sigma}{M(\sigma)(1-D)}\right]^{\beta} dN$$
(14)

where α depends on fatigue loading σ_{max} , σ , and β is the power-law fatigue exponent.

OTHER FAILURE MECHANISMS

Fiber-fiber abrasion and hysteritic heating may also contribute to the damage accumulation. Abrasion of fiber surfaces leads to fretting fatigue and increases the rope emperature. Creep deformation may be enhanced due to nysteritic heating of the ropes and effect of moisture on the mechanical compliance. The damage accumulation law may need to be modified to quantify contributions of these factors to failure.

The localized compression of synthetic ropes is of the greatest significant concern. If the fibers are subjected to global or localized compressive loads, failure is very likely to be governed by compression-induced failure mechanisms, and the damage law needs to be modified accordingly. Compression failure of fiber ropes is governed by formation and propagation of kink bands. The amount of lateral support of the neighboring fibers and fiber misalignment with the loading direction are critical. A small fiber misalignment may lead to an appreciable change in the compressive strength and reduction in the fatigue lives. Consequently, fiber construction and defects play a critical role in compression strength. High hydrostatic stresses at deep water provide additional lateral support to resist fiber kinking.

Since fatigue crack initiation is a surface driven phenomena, surface properties, such as surface roughness, fiber crystal structure, fiber and yarn make-up, fiber wear are important issues. Seawater exposure and associated chemical degradation of the fibers may also accelerate all of the damage mechanisms.

DISCUSSION ON MOORING ANALYSIS PROCEDURES

Dynamic behavior of vessels moored with synthetic ropes are being analyzed with approximate methods due to limitations of the mooring analysis programs to elastic materials and limited availability of visco-elastic material property data of the fiber ropes. Loading rate dependent stiffness of synthetic ropes is often described by three elastic constants: post-installation stiffness, drift stiffness, and storm stiffness. In this approach proposed elastic constants can be easily generated by small number of experiments and commercially available elastic mooring analysis methods can be fully utilized.

Since synthetic ropes have time-dependent material properties, original mooring configuration should be expected to change under both short-term and long-term applications. Time-dependent elongation of synthetic mooring ropes is a result of recoverable and irrecoverable events as quantified in Equations 1 and 2. The approach proposed in this study is suitable to quantify recoverable and irrecoverable elongation components of the mooring rope.

Failure of synthetic ropes is a damage accumulation process as outlined in the previous sections. Numerous mechanisms such as fatigue, creep, environmental attack, chemical degredation, and abrasion synergistically operate to govern failure of synthetic ropes. Depending on the rope material, rope size and construction, environmental conditions, and service conditions, one or more of these mechanisms may be operative. It should be noted that, each of the potential damage mechanisms are strongly related to the working stress level, therefore should be considered in assessing safety factors of the mooring systems.

Damage accumulation models developed for metals can not be used for synthetic ropes since they exhibit different failure mechanisms. For metals, elastic fatigue damage is typically proportional to the number of cycles. If the loading is elastic, cumulative damage accumulation under spectrum loading is calculated by linear Miner's rule. If the loading is elastic-plastic, nonlinear Miner's rule is used. As indicated in Equation 8, the damage accumulation law for synthetic ropes has a different form than the Miner's rule.

Especially for intermittent applications, the loading history has to be incorporated in the failure prediction models. Tracing load history and accompanying damage accumulation is critical when both creep and fatigue mechanisms are operative.

As an illustration, the total accumulated strain under a spectrum loading must be less than the ultimate strain of the rope (Fig. 4). The ratio of the accumulated strain to the ultimate strain defines the safety of the rope at its design life, i.e.,

$$S.F. = \frac{\varepsilon_f}{\varepsilon_a} \tag{15}$$

where S.F. is the safety factor at the end of the rope's design life. A typical load history of the rope may include installation loads, normal operating loads, short duration storm and hurricane induced loads and other miscellaneous loads (Fig. 5). The load characteristics for each case are different and yield to different strain accumulation rate. As an example, in Fig. 5 a schematic of the strain accumulation rate for a combination of these loading cases (denoted as spectrum loading in the figure) is compared with one with loads due to normal operations. Clearly, the design life due to spectrum loading would be lower than that due to normal operations. Given a load history, Equations 1, 2, and 8 may be used to determine both the total deformation of a synthetic rope and the time to attain this deformation, yielding the safety of the rope.

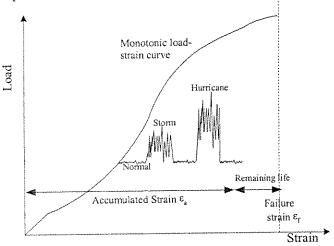


Figure. 4. Design deformation history of a synthetic mooring rope.

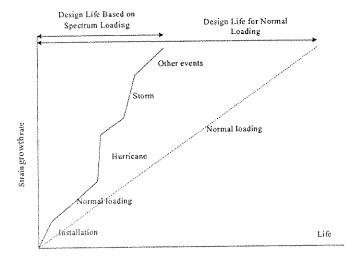


Figure 5. Deformation evolution of a synthetic mooring rope.

CONCLUSIONS

Advanced theories of time-temperature dependent rope mechanics can be used to accurately predict synthetic mooring rope load-deformation history as well as damage accumulation, failure and safety factors. Such approach can be used to improve the following factors in synthetic mooring rope design and analysis:

- · Better assessment of safety factors.
- Rope selection criteria
- Life prediction of the mooring system as a function of rope characteristics
- · Estimate remaining life and criteria for rope retirement
- · Inspection criteria
- Develop models to design rope end terminations.
- Life prediction of end terminations
- Temperature rises due to internal abrasion and its effects on creep.
- Improve rope selection and mooring system design guidelines.

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Modelling the Fire Response of Composite Structures for a Range of Thermal Conditions

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ABSTRACT

A model for the fire behaviour of thick composite laminates in hydrocarbon fires has been developed and experimentally validated by furnace fire testing. Composite panels in the form of thick laminates demonstrate an excellent thermal response under severe fire conditions. Heat transfer through the laminate is slow in comparison to metallic materials, which leads to long survival times and aids containment of the fire. The endothermic decomposition of the matrix provides the basic mechanism for slowing down the heat transfer through composite laminates, whilst the overall integrity of the structure is maintained for considerable time due to the non-combustible reinforcement.

INTRODUCTION

In every structural application for composite materials the issue of material response to thermal insult is one which must be addressed. As performance-led design procedures become widely accepted, composites are finding increasing application in new structures both on and off-shore. It is recognised that exceptional structural integrity can be achieved in certain types of composite structures under fire conditions. The combination of low thermal conductivity, resin endotherm effects and structural integrity combine to provide excellent fire characteristics for application as structural members, fire walls, blast panels and passive fire protection systems. The structural integrity under fire of liquid filled pipes or tanks has been reported in several instances [1,2]. Acceptance of composite materials in fire risk applications depends upon obtaining qualification of the composite system by satisfying strictly controlled standard tests. Standard testing involves small-scale tests such as non-combustibility, ignitability, surface spread of flame [3] and cone calorimetry [4] combined with large scale testing where the material is subject to 'realistic' thermal insult possibly under structural loading. Large-scale fire

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resistance tests include furnace tests under specified applied temperature / time curves such as the SOLAS curve [5], representative of a fire driven by cellulosic materials, or the more severe regime of the hydrocarbon fire curve [3,6]. Current interest in the offshore industry centres upon the response of materials to jet-fires [7]. A jet-fire consists of a turbulent flame from a jet of fuel material, which carries an initial momentum. The jet flame produces a large radiative heat flux combined with a physical erosive action on impinged surfaces.

Standard fire testing by qualified laboratories is seen as essential to the safe implementation of new materials within onshore and offshore applications. A predictive thermal model, validated against standard fire-test methods will help to minimise the number of standard tests required to qualify a new material. Furthermore, once the fire behaviour under the heat transfer conditions of the specific case of a standard furnace fire test are understood, then the model may be generalised to predict thermal response under other more realistic fire scenarios. Realistic thermal modelling of fire behaviour then provides the designer with the capability to demonstrate innovative, new designs with a predicted fire response and the minimum initial recourse to expensive standard fire testing.

EXPERIMENTAL: FURNACE FIRE TESTING

Experimental fire tests were carried out using a purpose built, stack-bonded ceramic wool lined furnace with an active volume of 3.375 cubic metres, gas-fired by a single portable burner. The test panels are mounted vertically in a specially designed frame forming the door of the furnace. A large single panel with an exposed surface area of 800x800 mm or alternatively 4 individual panels, each of 300x300 mm may be tested during each run of the furnace. The edges of the panels are protected to a depth of 50mm using a ceramic wool blanket.

The furnace is computer controlled to follow a specified temperature / time program. The reference temperature is taken as the mean value from four control thermocouples set 100mm from the hot face of the front panel. The bare wire furnace control thermocouples were insulated from and supported by high temperature steel tubing. The active tip of the probe projected from the end of the tube. For the purposes of model validation the furnace temperature was programmed to follow the NPD hydrocarbon fire curve [6], as shown in figure 1, which simulates the high rates of temperature increase experienced during severe hydrocarbon fires.

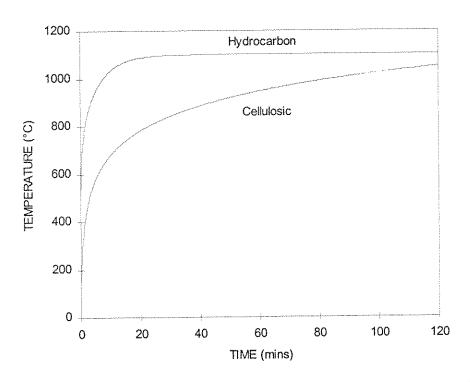


Figure 1: Temperature / time curves for the standard hydrocarbon and cellulosic fire tests.

Each test specimen was fully instrumented with thermocouples on the hot and cold faces. In addition for some of the thicker laminates, inter-laminar thermocouples were set inside the samples during manufacture. The output of each individual thermocouple was continuously monitored throughout the test runs and recorded using a computer data logging system. On the hot face, thermocouple contact could only be maintained at the start of the test, since the face layer is rapidly burnt away. Copper disc thermocouples were used on the cold face, covered and held in position by insulating pads. If the thermocouples were bonded on with epoxy resin, they tended to drop off in the later stages of the test. Better performance was found using a paste of sodium silicate and ball clay, provided the contact area was lightly roughened first.

The temperature response of a 22mm thick glass woven roving / isophthalic polyester panel is shown in figure 2. The furnace temperature increases rapidly to a limiting value of 1100°C following the NPD hydrocarbon curve standard as shown in figure 1. The panel response is shown by four separate traces, representing the temperatures at quarter points through the thickness and at the cold face. The cold face temperature increases almost linearly throughout the fire test, remaining below 200°C after 40 minutes.

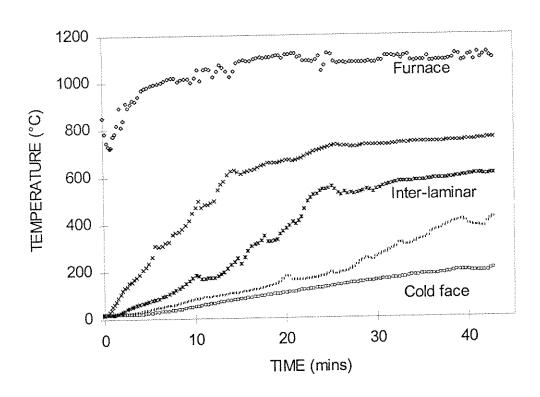


Figure 2: A typical hydrocarbon curve furnace fire test result for a 22mm thick polyester / glass woven roving laminate with a volume fraction of 0.5. The top curve is the furnace temperature, followed by three inter-laminar thermocouple outputs from quarter points through the thickness and finally the cold face temperature.

An insulation failure criterion was applied to the furnace fire tests. The panels were considered to have failed when the cold face temperature had reached 160°C (a cold face temperature rise of 140°C above ambient) and the tests terminated before full penetration of the panels occurred.

Experimental relative fire barrier performance data derived from hydrocarbon curve furnace fire testing is shown in Figure 3. The standard development material has been taken as isophthalic polyester / glass woven roving with a glass volume fraction of 55%. The most successful materials in terms of thermal barrier performance are those with the highest endothermic contribution. For panels with an aramid content the reinforcement also decomposes endothermically this is illustrated by the advantageous thermal barrier performance observed in Figure 3, especially when aramid is combined with glass reinforcement for added structural integrity.

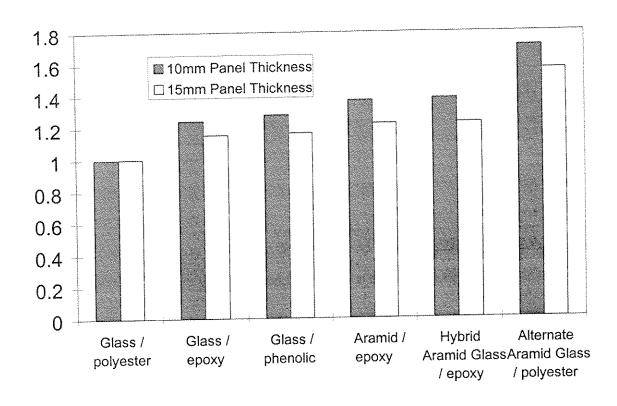


Figure 3: Laminated panel response to hydrocarbon curve furnace fire tests ranked as a Relative Fire Barrier Performance Index. The ranking is the time required for the cold face to reach 160°C normalised with reference to standard polyester glass woven roving laminates.

In the furnace fire tests the panel cold face is exposed to stationary air, which removes very little heat. If heat is actually removed from one side of the laminate, i.e. there is forced convection at the boundary, the time to failure can be even further prolonged [8]. This effect can usefully be employed with composite pipework containing a stationary, or better still, flowing fluid, and is one of the reasons why GRE pipes have begun to be so widely used for offshore fire-water systems.

MODELLING THE MATERIAL RESPONSE TO FIRE

Mathematical models of the fire behaviour of combustible materials have been developed from the unsteady state heat equation (1) by including terms describing the ablative processes which take place [9,10,11].

$$\frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \stackrel{\bullet}{q} = \rho c_p \frac{\partial T}{\partial t} \tag{1}$$

Typical reinforcements such as E-glass are non-combustible and remain structurally stable within the temperature regime of most non-erosive fire scenarios. The ablative behaviour under fire conditions of glass fibre reinforced polymer composites involves two main processes that significantly affect the heat transfer mechanism through the material. The most important effect is the 'cracking' of the resin component of the composite. This chemical reaction is an endothermic decomposition process that effectively removes heat energy from the fire in order to physically break down the polymer. The second important process involves mass transfer of the gaseous reaction products by diffusion away from the reaction front removing energy from the remaining material. Although the endotherm and subsequent mass transfer inhibit the flow of heat through the composite, the combustion and subsequent heat release from the gaseous reaction products after diffusion away from the laminate surface will then add to the incident fire. When the composite material forms a small part of the fire inventory, as would be the case in a well developed hydrocarbon fire, the heat release due to the composite remains small compared to the overall incident thermal energy.

The energy flux involved in the decomposition of the combustible components of the composite material can be expressed mathematically by the net heat of decomposition multiplied by the rate of decomposition. The rate of a chemical reaction may be conveniently expressed using an Arrhenius rate expression of the form shown in equation 2 assuming no expansion of the material. [12]

$$\frac{\partial \rho}{\partial t} = -A \left[\frac{(\rho - \rho_f)}{\rho_o} \right]^n e^{(-E/RT)} \tag{2}$$

Where:

 ρ , t and T are the density, time and temperature variables respectively A, E and n the rate constant, activation energy and order of the reaction R is the gas constant

The energy transferred by convection due to the gaseous reaction products diffusing away from the reaction front can be expressed as the product of the gas enthalpy and mass flux. Assuming that all of the gaseous reaction products immediately diffuse away from the reaction front, then by conservation of mass, the mass flux of gas must equal the rate of material decomposition. Thus the mass flux and hence the effect of convection of the reaction products can be calculated from a knowledge of the reaction rate as expressed in equation 2 above. That is for a one-dimensional problem [10]:

$$\dot{M}_G = \int_{x}^{L} \frac{\partial \rho}{\partial t} dx \tag{3}$$

Introducing the endothermic decomposition and mass flow effect terms into equation (1) and assuming that thermal equilibrium exists between the decomposing composite material and the resultant gases leads to a one-dimensional non-linear partial differential equation which models the thermal response of combustible composite systems.

$$\rho C_{P} \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) - \dot{M}_{G} \frac{\partial}{\partial x} h_{G} - \rho A e^{-\frac{E}{RT}} \left(Q_{P} + h_{C} - h_{G} \right)$$
(4)

where:

T, t and x are temperature, time and through-thickness coordinate, respectively

 ρ , $C_{\rm P}$ and k are the density, specific heat and conductivity of the composite $\dot{M}_{\rm G}$ is the mass flux of volatiles from the decomposition reaction $h_{\rm C}$ and $h_{\rm G}$ are the respective enthalpies of the composite and evolved gas

 $Q_{\rm p}$ is the endothermic decomposition energy

 \overline{A} , E and R are the rate constants for the decomposition reaction and the gas constant.

The three terms on the right hand side of equation (4) relate to heat conduction, volatile convection and endothermic resin decomposition, respectively. The rate constants for the decomposition term are estimated from thermo-gravimetric measurements on laminate samples.

MODEL IMPLEMENTATION

The solution of equations (3) and (4) with suitable boundary conditions provides the basis for a one dimensional thermal response model for the fire behaviour of composite materials [10]. A numerical solution has been implemented, which with experimental validation provides a convenient, economic means of predicting the fire behaviour of laminated composite systems. An explicit finite difference scheme has been used, the time derivative term in the governing equation is represented by forward differences whilst the spatial variables are represented by central differences.

Boundary Conditions

The boundary conditions are the general conditions of convective and radiative exchange at the free panel surfaces with the convective heat transfer coefficients tuned to the fire

conditions of interest. The applied boundary conditions for the panel surfaces take the general form:

$$-k\frac{\partial T(0,t)}{\partial x} = \overline{h}_{\varepsilon}[T_{S} - T_{s}] + \sigma[\varepsilon_{f}T_{S}^{4} - \varepsilon_{s}T_{s}^{4}]$$
 (5)

Where.

 T_s denotes the surrounding temperature

 T_s the surface temperature

 \overline{h}_{c} the heat transfer coefficient for convection

 \mathcal{E}_{f} , and \mathcal{E}_{s} , the emissivity of the surroundings and panel surface respectively

 σ the Stephan-Boltzmann constant

The two terms on the right hand side of equation 5 represent the convective and radiative contributions to the heat transfer at the material surface. The form of the convection term depends strongly upon the geometry and orientation of the surface of interest. For the purposes of modelling experimental furnace tests an empirical relation defined for convective transfer to a vertically orientated flat panel has been adopted [12]. The radiative exchange at the material surfaces can be modelled for the specific test furnace to a first approximation by applying suitable view factors and emissivity values for the furnace and test specimen.

Material Properties

Description of the kinetic properties requires a knowledge of the decomposition reactions taking place which then allows prediction of the rate of change of mass of the composite. The transport properties of the composite will change as the decomposition reaction progresses through the thickness of the laminate, but they are ill-defined for the material in the process of decomposition. The derivation by the computer program of the materials properties in the reactive region has been greatly simplified by assuming the region instantaneously reacting is small and that the transport properties can be represented by simple average values.

Kinetic Properties

Thermo-Gravimetric Analysis (TGA) has been carried out to investigate the kinetics of the polyester decomposition reaction. There are several factors which introduce uncertainty into the results of TGA investigations such as specimen particle size and surface area, but for the purposes of modelling the fire behaviour of polyester resin composite laminates we have concentrated upon the general form of the reaction and the trends observed. The TGA measurements under idealised, laboratory conditions provide enough data to fit an Arrhenius rate equation (equation 2) to the material behaviour and also provide a measure of the amount of carbonaceous char left behind when the resin is spent.

The kinetics of the decomposition reaction during a hydrocarbon fire test are illustrated in Figure 4. The rate parameters, A and E, in equation (1) are obtained experimentally by thermo-gravimetric analysis at a fixed heating rate (solid curve Figure. 4(a)). The dotted lines in Figure 4(a) are the calculated resin decomposition curves through the laminate thickness for the variable heating rates applied during a hydrocarbon curve fire test. The differences between the experimental and calculated TGA curves are due to the variation of heating rates during a hydrocarbon fire test. The calculated variation of the effective heating rate during a hydrocarbon curve fire test is plotted in Figure 4(b) for through thickness positions in an 11mm thick polyester / glass panel. The highest heating rate is at the hot face as expected and the test is predicted to have reached a steady state after ≈16 minutes.

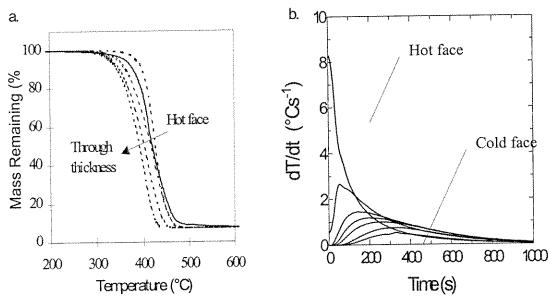


Figure 4: (a) Comparison of experimental thermo-gravimetric data collected at 25°C/min in a nitrogen atmosphere (solid line) with the calculated mass loss at points through the laminate thickness (dotted lines). (b) The calculated effective heating rates for a polyester / glass laminate during a hydrocarbon curve fire test. The highest rate is at the surface, decreasing at points through the thickness.

Transport Properties

As the decomposition reaction progresses the transport properties of the composite will vary dynamically according to the local state of the resin as illustrated schematically in figure 4. As the fire progresses region 1 will increase and region 3 will decrease in size as region 2 moves through the thickness of the laminate. By assuming that the composite components are intimately mixed and orientated in a plane perpendicular to the through-thickness direction we can disregard further details of the composite architecture. The transport properties are then a function of the constituent volume fractions only. The temptation, in finite difference solutions to the heat transfer equation, is to disregard the

temperature dependence of the materials properties. The thermal conductivity of polyester resin has only weak temperature dependence over the temperature range of useful application [13], so for heat transfer analysis an average constant value may be assumed. In modelling the thermal response of a combustible system, the changes in properties through the thickness of the material depend not only upon the different temperatures but also the state of the resin decomposition reaction locally, therefore the finite difference solution must include the change in the properties.

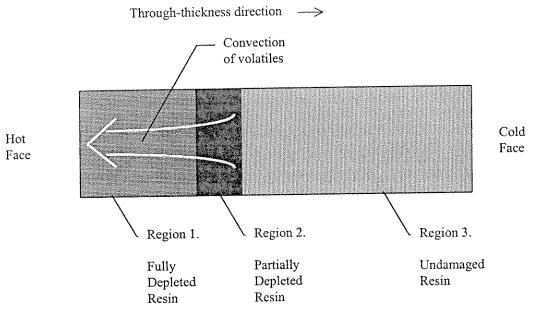


Figure 5: Schematic of the fire model

We can calculate the properties of the composite locally as the resin decomposes by applying a suitable rule of mixtures. As the resin systems under consideration were commercial grades, the transport properties of the undamaged composite materials under test were derived from literature sources [12-15] and manufacturers specifications [16]. The residual properties after decomposition were estimated by considering the typical properties of the dry glass fibre reinforcement.

Thermal Conductivity

The thermal conductivity of a laminated panel in the through-thickness direction is derived from the conductivities of the fibre and matrix components using a rule of mixtures approach. The temperature dependence of the thermal conductivity is modelled by a linear least squares fit to published experimental data [13].

$$\frac{1}{k_c} = \frac{V_f}{k_f} + \frac{V_m}{k_m} \tag{6}$$

where: k_f , k_m and k_c are the thermal conductivity's of the fibres, matrix and composite respectively, V_f and V_m are the fibre volume fraction and the matrix volume fraction of the composite.

To model the thermal conductivity of the composite as the resin is decomposed dynamically into the three regions illustrated in figure 5, equation (6) is applied node by node. Region 1 where the resin is completely spent has a thermal conductivity approaching that of the reinforcement. The definition of the transport properties within region 1 can be complicated by the amount of delamination present. For our purposes an average value has been adopted, aiming to model typical polyester /glass behaviour. Within region 2 the resin decomposition reaction is in progress so the thermal conductivity is less well defined, but applying equation 6 with the changing fibre and matrix volume fractions gives an average value of the thermal conductivity according to the extent of the reaction. The undamaged material maintains the original composite value modified solely by the change in temperature.

Specific Heat

The specific heat capacity of the composite material is determined using a weighted average of the form:

$$c_{com} = \frac{c_f \rho_f V_f + c_m \rho_m V_m}{\rho_f V_f + \rho_m V_m} \tag{7}$$

Where:

 c_{f} , c_{m} and c_{com} are the heat capacities of the fibres, matrix and composite V_{f} , V_{m} , ρ_{f} and ρ_{m} are the respective volume fractions and densities of the fibres and matrix

Again the value varies according to the progress of the decomposition reaction locally within the laminate the value adopted being weighted by the effective mass of the components at the specific point in the laminate. The temperature dependence of the resin specific heat capacity is modelled using a second order polynomial fit to published data [13].

MODEL VALIDATION

The computer implementation of the thermal model has been validated by comparing the calculated thermal response with the experimentally measured response during a hydrocarbon curve fire test, for a range of panel thicknesses. The heat transfer conditions at the panel hot face and cold face remain constant, for each fire test as the same furnace

conditions are employed. The only variables required for input into the computer model are the fibre volume fraction and the thickness of the panel. Figure 6 shows the comparison for three individual panel thicknesses of 11 17 and 22 mm. The dotted lines are the calculated temperatures and the solid lines the experimentally measured temperatures. For each panel thickness the computer model predicts the cold face temperature response very accurately.

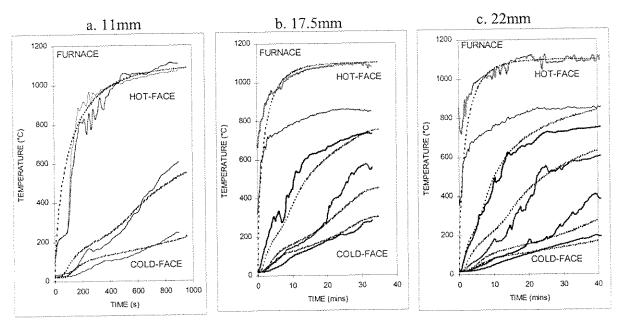


Figure 6: Experimental hydrocarbon curve furnace fire tests results (solid lines) for isophthalic polyester / glass woven roving laminated panels and corresponding one-dimensional modelled response (dotted lines). Intermediate curves are inter-laminar temperatures.

The low thermal conductivity of the undamaged composite material combined with a relatively high specific heat capacity slows down the heat transfer through the material. As the resin component of the composite burns, it leaves behind a carbonaceous char which loosely binds the glass reinforcement layers together. This resultant structure helps shield the remaining composite material, also slowing down the rate of heat transfer. But, the transport properties of the composite material alone do not explain the observed cold face temperature response. The cold face temperature rise is lower than would be expected from consideration of the materials properties alone. The reason that the composite panels exhibit a slow burn-through effect is that the resin matrix decomposes endothermically as the temperature is increased in the fire. The endothermic decomposition process effectively subtracts heat energy from the composite material, heat which otherwise would be conducted through to the cold face resulting in an increased temperature throughout the laminate. The decomposition reaction also produces gaseous products, which diffuse away from the reaction front again providing a mechanism to remove energy from the decomposing material. The structure of the

composite material, combining non-combustible reinforcement with a combustible matrix enables the composite panel to retain enough structural integrity well for the resin endotherm effect to take place.

The effect of including the resin decomposition and mass flow effects in the thermal response calculation is illustrated in figure 7. The solid lines are the thermal response of a panel using only the transport properties. The dotted lines include the resin endotherm effect and the mass flow effects. The dotted lines at each point through the laminate begin to diverge away from the solid lines as that part of the structure begins to react. As the time progresses, this effect lowers the temperature observed through the laminate thickness. At the cold face the effect is seen to be producing a cooling effect after approximately 10 minutes of the hydrocarbon curve fire test. Significantly increasing the survival time of the laminate during the fire test.

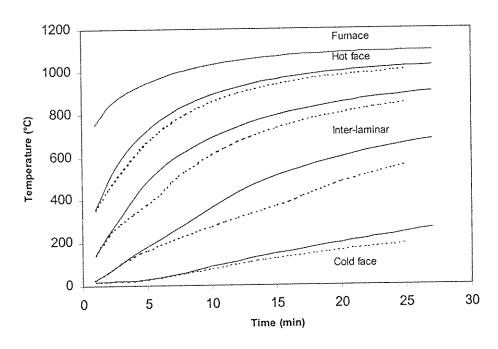
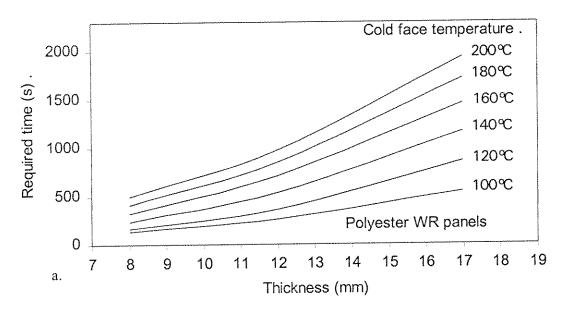


Figure 7: Calculated temperature response of a 20mm thick polyester glass panel to a hydrocarbon fire with (dotted lines) and without (solid lines) the resin decomposition term.

APPLICATION OF THE MODEL TO DIFFERENT THERMAL CONDITIONS

The thermal model may be used to provide design information for the use of composite materials in any fire sensitive application. The difficulty in applying the model to different fire scenarios is in accurately defining the relevant heat transfer boundary conditions.

Design charts prepared using the validated computer model are shown in Figure. 8. Figure. 8(a) allows polyester woven roving laminate thickness' to be defined by the allowed cold face temperature rise in a hydrocarbon fire, while Figure. 8(b) shows the cold face response of laminates to a predetermined constant heat flux. The constant heat flux boundary condition is the first approximation to the boundary conditions relevant to jet fires. Recent analysis of jet fire data [17] has indicated that the extremes of thermal response of composite materials to jet fires can be successfully modelled by combining a maximum heat flux boundary condition with a maximum erosion physical erosion rate.



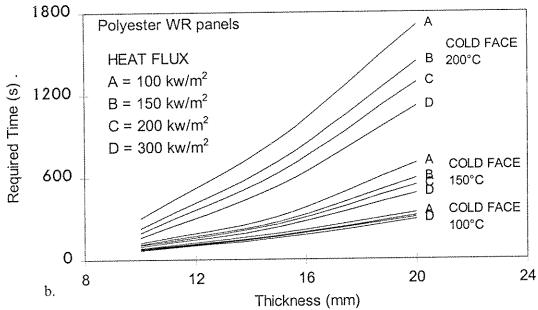


Figure 8: Design charts for polyester glass WR laminates prepared using the thermal model. (a) Hydrocarbon curve fire response - thickness required for specified temperature. (b) Cold face temperature response for specified incident heat flux vs. Thickness.

The model can also be extended to two-dimensions to calculate the thermal response of realistic structural combinations. The thermal response to severe fires of sections such as corners or stiffeners in sandwich structures can then be reliably simulated and this data

can be used to help predict the thermal / mechanical response of the structure. Figure 9 shows the temperature response of a composite rib structure after 4 minutes engulfed in a hydrocarbon fire.

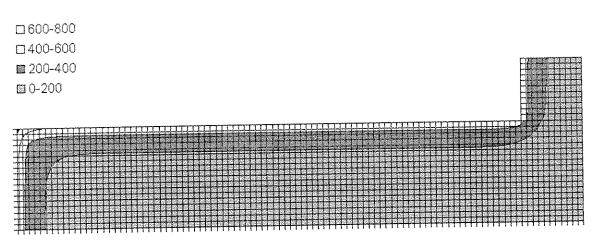


Figure 9: Contour map showing the temperature at an internal and external corner for a composite rib engulfed in a hydrocarbon curve fire test.

CONCLUSIONS

Organic matrix composites have considerable potential for use in large load-bearing structures that may be subject to fire. When used in sufficiently thick sections these materials are capable of withstanding severe temperatures and ablative effects by virtue of the endothermic nature of the resin decomposition process and low thermal conductivity combined with good structural integrity from non-combustible reinforcement.

The thermal response of composite systems subjected to severe hydrocarbon fire conditions can be accurately predicted using an experimentally validated thermal model which provides basic data for performance based design.

ACKNOWLEDGMENTS

The fire modelling work reported here has been carried out in collaboration between the Newcastle Centre for Composite Materials Engineering and Professor J M Davies' Fire Research Group at Manchester University. The following organisations, which have supported the Marinetech Research Composites Offshore programme, have contributed greatly to the work presented here. Their support is gratefully acknowledged: AGIP (UK), Amerada Hess, Ameron bv, Amoco Research, Balmoral Group, Bow Valley Petroleum, BP Exploration, Brasoil, British Gas, Ciba, Conoco, Defence Research Agency, Dow Chemicals, DRA, EDF, Elf (Aquitaine), Enichem (SPA), Exxon, Hunting Engineering, Kerr McGee Oil (UK) Ltd, MaTSU, Centre for Marine and Petroleum

Technology Ltd., Maunsell Structural Plastics, Mobil Research and Development Ltd, Norsk Hydro, UK Ministry of Defence (Navy), UK Offshore Supplies Office, Phillips Petroleum, Shell, SLP Engineering Ltd, Statoil, Total Oil Marine, UK Department of Energy, VSEL and Vosper Thornycroft.

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Certification Agency Perspective on Composites in the Offshore Industry

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ABSTRACT

This paper describes ABS's involvement in both the Offshore Industry and with composite materials used in the maritime community. ABS has published Rules for the Building and Classing of MODU's and Offshore Installations since the late 1960's, and is concurrently an industry leader in the development of requirements for the safe use of composites in the marine industry. ABS maintains this position at the leading edge of technology by participating in various research panels and constantly updating our Rules to reflect the increased use of composites in the offshore industry.

Introduction

The American Bureau of Shipping (ABS) was founded in 1862 and today provides classification, inspection, certification and quality assurance (QA) services to the Marine and Offshore communities. Functioning as an independent, non-governmental and not-for-profit organization ABS provides an unbiased, objective service to its clients.

The mission of ABS is to serve the public interest as well as the needs of our clients by promoting the security of life, property and the natural environment primarily through the development and verification of standards for the design, construction and operational maintenance of marine-related facilities. In order to carry out this mission, ABS publishes over 50 rule books, guides and related publications covering all types of vessels, offshore structures, marine facilities and equipment. ABS Rules are accepted worldwide as recognized international standards. In addition to the application of ABS rules, ABS is also recognized by national administrations throughout the world to issue certifications and carry out surveys on their behalf. ABS has close working relationships with the U.S. Coast Guard, U.S. Minerals Management Service, U.K. Health and Safety Executive, Norwegian Maritime and Petroleum Directorates, as well as many others. ABS has over 150 offices in 84 countries worldwide to provide a whole range of services to the Offshore industry.

ABS in the Offshore Industry

ABS became involved in earnest in the Offshore industry in the early 1960's and developed and issued the first "Rules for Building and Classing Offshore Mobile Drilling Units" in 1968. Not long after this, the International Maritime Consultative Organization (IMCO, later IMO) developed its Rules for MODU's. The 1968 ABS Rules were used by IMCO as a basis for this development.

Since 1968 ABS has been the world leader in Classification and Certification of Mobile Offshore Drilling Units and other Offshore structures such as fixed platforms, Floating Production, Storage and Offloading Systems (FPSO's), Single Point Moorings (SPM's), Undersea Pipelines, Tension Leg Platforms (TLP's) and most recently the first production Spar, Oryx's Neptune Spar which is Classed by ABS. In addition to Classing new construction projects, in recent years ABS has been involved with numerous conversions of existing floating and bottom founded MODU's and Tankers into Production Units.

ABS Rules and Guides for the use of Composites

ABS's position as the world leader in providing Classification and Certification services to the Offshore Industry makes ABS uniquely qualified to discuss regulatory aspects relative to the use of composite materials in the offshore marketplace. ABS published its first rules for Classing Fiber Reinforced Vessels in 1978. This rule book was primarily written for commercial vessels that are constructed with the basic composite materials of chopped strand mat and woven roving fabrics.

Since that first Rule book featuring basic composites, ABS strives to keep up with the new technologies being developed. In 1986 we published the Guide for Building and Classing Offshore Racing Yachts, this guide contained basic scantling requirements for sandwich laminates and the newer off-axis materials. With the success of this guide ABS developed the Guide for Building and Classing High Speed Craft and Motor Pleasure Yachts in 1990. These Guides included requirements for building vessels with steel, aluminum, and composites, and allowed for materials other than e-glass. At this time, ABS started to recognize the importance of the building process in fiber reinforced plastic (FRP) construction.

Recently ABS published the 1997 Guide for Building and Classing High Speed Craft. This guide and the upcoming revised Motor Pleasure Yacht Guide allow for state of the art materials (Kevlar and carbon fibers) and state of the art construction processes (resin infusion, pre-pregs, etc.).

Currently ABS requirements for offshore structures (both MODU's and Offshore Installations) only allow for a small amount of composites to be used on the structure. ABS always keeps an open mind to new technologies, and as more composites suitable for use in offshore platforms become available, the rules will be revised to reflect current

practices. As the technology continues to develop, ABS will allow the use of composites on offshore structures provided they can meet the loading requirements, national regulations (i.e. MMS and USCG) and international conventions (1989 IMO MODU Code) as applicable.

CURRENT REQUIREMENTS

Mobile Offshore Drilling Units

As explained in the introduction, ABS has been classing MODU's since 1968, and the current requirements are stated in the 1997 Rules for Building and Classing Mobile Offshore Drilling Units. This Rule book is divided into four parts consisting of survey, materials, hull construction and equipment, and machinery requirements. The part on hull construction and equipment has specific requirements for self-elevating drilling units, column-stabilized drilling units, and surface-type drilling units. There are also sections for common structures, stability, welding and structural fire protection (see below). The machinery section contains rules for electrical, fire protection, mechanical systems, and piping (including plastic piping, see below).

These Rules only have requirements for structures built from steel, however this does not limit the use only to steel. ABS has always allowed for non-conventional material to be used. The Rules have an independent section defining the environmental loads, and it would not be difficult to apply these loads as well as other requirements to a material other than steel.

Offshore Installations

The current ABS Rules, the 1997 Rules for Building and Classing Offshore Installations, supersedes the 1983 rules by the same name. This Rule book is divided into four parts: 1) Classification, Testing and Surveys, 2) Materials and Welding, 3) Design, and 4) Extension of Use and Reuse. The design requirements in these Rules have been posed in terms of existing methodologies and their attendant safety factors, load factors or permissible stresses which are deemed to provide an adequate level of safety. Primarily, the use of such methods and limits in these Rules reflect what is considered to be the current state of practice in offshore installation design. At the same time, it is acknowledged that new methods of design and construction are constantly evolving along with new structural types, materials, or new uses for established structural types and In recognition of these facts, the Rules specifically allow for such components. innovations. The application of these Rules by the Bureau will not seek to inhibit the use of any technological approach which can be shown to produce an acceptable level of safety.

Plastic Piping

Until recently, ABS Rules for non-metallic piping limited its use only to non-critical systems and in areas with minimal fire risk. There has been considerable work in the marine industry over the last ten years or so to develop standards that would permit wider usage of non-metallic piping materials. Two independent organizations, the International Maritime Organization (IMO) and the International Association of Classification Societies (IACS) have done considerable work on developing standards for non-metallic piping. Although independent organizations, IMO and IACS shared their development work and the resulting documents from both bodies are essentially the same with only minor differences. The IMO document is entitled "Guidelines for the Application of Plastic Pipes on Ships", it is Resolution number A.756(18) and it was adopted by IACS on 4 November 1995. The IACS document is entitled "Production and Application of Plastic Pipe on Ships": it is IACS unified requirement P4 and is dated 1996.

ABS as a member of IACS participated in the development of these standards and in 1997 incorporated them into the ABS Steel Vessel Rules and MODU Rules. These Rules address design, installation, manufacturing, bonding procedures and testing. The new Rules permit a much wider range of application of non-metallic pipe than what was permitted under the previous Rules. At the heart of the New Rules is a Fire Endurance Matrix which specifies the level of fire endurance required for different systems at different locations. A non-critical system installed in an area of minimal fire risk would require little or no fire endurance properties whereas a critical system in an area with a higher fire risk would require a higher level of fire endurance. There are six possible entries in the fire endurance matrix as follows:

Matrix Entry	Definition
L1	Fire Endurance Test in Dry Conditions - 60 minutes
L2	Fire Endurance Test in Dry Conditions - 30 minutes
L3	Fire Endurance Test in Wet Conditions - 30 minutes
0	No Fire Endurance Required
NA	Not Applicable
X	Metallic Materials Required

A copy of the entire fire endurance matrix is included as an attachment to this paper.

Note that these Rules are intended for application on Ships and MODU's, but wider application to other types of Offshore Structures is anticipated. As a point of interest, and as an example of the wider applications for non-metallic pipe we are beginning to see, on a number of recent offshore projects, the U. S. Coast Guard has accepted the use of fiberglass reinforced piping in the firemain. ABS has also accepted this application based on the U. S. Coast Guard approval.

The offshore marketplace is constantly changing and the need for corrosion resistant lightweight materials is increasing. ABS looks forward to working with the composite industry and the offshore industry to ensure that we continue to service the needs of our clients without impairing the safety of marine and offshore installations.

Structural Fire Protection

Currently one of the major obstacles for the use of composite materials on ships is the structural fire protection requirements stated by the IMO (International Maritime Organization) in the 1974 SOLAS (Safety of Life at Sea) Convention. Similar structural fire protection requirements are also in place for offshore structures as stated in the IMO MODU code and in our 1997 Rules for Building and Classing MODU's. These requirements are primarily for protection of high fire risk spaces, such as machinery spaces and hazardous areas, or for protection of accommodation spaces and escape routes such as stairways and corridors,. [There are no structural fire protection requirements for the primary structures (below the waterline?), risers, and tethers.]

The IMO currently states that the areas of high fire risk or areas requiring protection (see items stated above) are to be constructed of a material that is "steel and equivalent". With the current surge of composite technologies and the ever recent demands to use composites on ships the IMO has published the "Interim Guidelines on the Test Procedure for Demonstrating the Equivalence of Composite Materials to Steel under the Provisions of the 1974 SOLAS Convention". This document establishes criteria for the acceptance of composite materials for use onboard ships. The difficult part of these requirements is that the composite material must be classified as a *non-combustible* material, and currently there are no composite materials or composite plus insulation that can meet this standard. Since the requirements set forth by this document are very difficult, there is a large amount of research being done to have a composite panel pass this criteria.

Another document that is published by the IMO is the 1994 IMO High Speed Code. This document is part of SOLAS and is written for high speed vessels that operate with in relative proximity to a port of refuge. The High Speed Craft Code is more liberal with the use of composites, and allows for the use of combustible structural materials providing that they meet the requirements as a *fire restricting* material. These requirements are also outlined by the IMO in the "Adoption of the International Code for Application of Fire Test Procedures" and are also very difficult to meet, however there are options available to meet this criteria, especially by using the some of the various types of insulation that are available.

FUTURE TRENDS

ABS has seen composites used in piping systems, gratings, and cable trays on ABS classed MODU's and Offshore Installations. With current developments being made in composite risers, tethers, and structures, ABS will continue to keep our requirements current. We are currently working with industry on several programs designed to further develop the use of composite materials in the marine industry.

Maritech BAA94-44 Composite Superstructures

This Maritech program is tasked to develop a cost effective method for building composite superstructures for ships. The members of this group have developed a construction technique by using prefabricated panels (both sandwich and single skin), pultruded composite sections, and preformed composite stiffeners. The superstructures are constructed using a "lego block" technique by using the pultruded sections to join panels, and adhesives to bond stiffeners to the panels. Currently the project team is planning on building a sample structure using the tools that have been developed. The designs for this structure are in the final stage, and it is the idea of the team to showcase any other composite innovations in the final structure. For example, it is planned to show composite piping that was originally developed for the offshore industry, and fire protective insulation that was developed by the aerospace industry.

In concept, this method for quickly and cost effectively building a strong and light superstructure for a ship can easily be transferred to the offshore industry for platform structures and accommodation spaces.

SNAME HS-9 Committee

ABS is currently serving as chairman of the SNAME HS-9 committee on composite materials. There are currently two major areas of study under this panel: 1) The fire characteristics of composites, and 2) Panel testing of composites.

The fire study is currently working on similar tasks as the Maritech project, however it has mainly been focused on study of the experimental effects of fire on composites. Currently under the IMO High Speed Craft Code the panel must be tested by the "Room Corner" burn test. This test involves building an 8' x 8' room with the material and then placing a fire load in the corner of the room. The flux of the fire is then altered during the course of the test, and the amount of smoke and flame spread is measured during the course of the test. This type of test is very expensive, and the main research of this study is to determine if there are any correlation between smaller scale fire tests and the results of the larger scale room corner test. This will allow for a more cost effective method for determining if a fire protection scheme is worth having tested by the Room Corner Test. No major results from this research has been published.

The panel test program is trying to develop an ASTM test procedure for panels. The test fixture uses a water bladder to apply a load onto a panel with fixed ends. The pressure versus deflection curves are then used to determine the ability of a panel to absorb the load. This particular test program has shown the benefits of linear foam cores and off-axis laminates that currently do not test favorably with simple beam testing.

Conclusions

ABS's involvement has been in extensive in both the offshore industry and with the development of composite materials. With the recent technological advancement of composite materials in the offshore industry ABS feels the need to take a proactive role in the developments by serving on various industry and academic groups. ABS is committed to continuing as an industry leader in the offshore and composite industries, and as these industries continue to merge together ABS will take an active role in providing safe requirements for their use.

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ATTACHMENTS

[A] Plastic Piping Fire Endurance Requirements Matrix, Table 4/4.2 from the ABS Rules for Building and Classing Mobile Offshore Drilling Units, 1997

FIRE ENDURANCE REQUIREMENTS MATRIX Table 4/2.2

		LOCATION							
	PIPING SYSTEMS	A	В	С	D	E	F	G	H
FI A	MMABLE LIQUIDS								
1	Oil (flash point ≤ 60C (140F))	NA	NA	0	NA	0	0	NA	Ll2
2	Fuel oil (flash point > 60C (140F))	X	X	NA	0	0	0	Li	LI
3	Lubricating oil	X	X	NA	NA	NA	0	Ll	Ll
4	Hydraulic oil	X	X	0	0	0	0	Ll	Ll
	WATER (See Note 1)								L1
5	Bilge main and branches	Ll	Ll	NA	0	0	0	NA	L1
6	Fire main and water spray	Ll	Li	NA	NA	0	0	X	
7	Foam system	Ll	LI	NA	NA	NA	0	Ll	L1 L3
8	Sprinkler system	Ll	Ll	NA	NA	0	0	L3	L3 L2
9	Ballast	L3	L3	0	0	0	0	L2	L2 L2
10	Cooling water, essential services	L3	L3	NA	NA	0	0	NA	L.2 0
11	Non-essential systems	0	0	NA	0	0	0	0	U
	ESH WATER					,		1 + 2	1 17
12	Cooling water, essential services	L3	L3	NA	0	0	0	L3	L3
13	Condensate return	L3	L3	NA	NA	NA	0	0	0
14	Non-essential systems	0	0	NA	0	0	0	U	
SA	NITARY/DRAINS/SCUPPERS					·			1 0
15	Deck drains (internal)	Ll ³	L1 ³	NA	0	0	0	0	0
16	Sanitary drains (internal)	0	0	NA	0	0	0	1 U	1 0
17	Scuppers and discharges (overboard)	01,5	01,5	0	0	0	0	U'''	\ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \
VE	NTS/SOUNDING		<u></u>	T 2	T	T 0	0	1 0	1 0
18	Water tanks/dry spaces	0	0	0	0	0	0	$\frac{1}{x}$	$+\frac{v}{x}$
19	Oil tanks (flashpoint > 60C (140F))	X	X	X	0 NA	0	0	⊢ ∧ NA	$+\frac{\lambda}{x}$
20	Oil tanks (flashpoint ≤ 60C (140F))	NA	NA	0	INA	U	_ <u>'</u>	1 11/1	<u></u>
MI	SCELLANEOUS	· · · · · · · · · · · · · · · · · · ·	1 7 77	1 374	1 0	T 0	1 0	T.14	LL
21		L1 ⁴	Li ⁴	NA	1 0	0	1 0	+ 0	1 0
22	Service air (non-essential)	0	0	NA	NA	NA	10	10	+
23		0	0	NA 0	NA 0	NA 0	1 0	106	+ 0
24	Auxiliary low pressure steam (Pressure ≤ 7 bar (7 kgf/cm², 100 psi))	L2	L2	0	U		l "	<u> </u>	

A	Category A machinery spaces	L
В	Other machinery spaces	
C	Oil tanks (flashpoint ≤ 60C (140F))	L
D	Fuel oil tanks (flashpoint > 60C (140F))	
E	Ballast water tanks	L
F	Cofferdams, void spaces, pipe tunnels and	
ducts		0
G	Accommodation, service and control spaces	N
H	Open decks	X

Abbreviations

- L1 Fire endurance test in dry conditions, 60 minutes, in accordance with 4/2.17.7
- 2 Fire endurance test in dry conditions, 30 minutes, in accordance with 4/2.17.7
- .3 Fire endurance test in wet conditions, 30 minutes, in accordance with 4/2.17.8
- No fire endurance test required
- NA Not applicable
- X Metallic materials having a melting point greater than 925C (1700F).

Notes

Locations

- Where non-metallic piping is used, remotely controlled valves are to be provided at the unit's side. These valves are to be controlled from outside the space.
- Remote closing valves are to be provided at the tanks.
- For drains serving only the space concerned, "0" may replace "L1".
- When controlling functions are not required by statutory requirements, "0" may replace "L1".
- Scuppers serving open decks in positions 1 and 2, as defined in Regulation 13 of the International Convention on Load Lines, 1966, are to be "X" throughout unless fitted at the upper end with the means of closing capable of being operated from a position above the freeboard deck in order to prevent downflooding.
- For essential services, such as fuel oil tank heating and whistle, "X" is to replace "0".



COMPOSITE MATERIALS FOR OFFSHORE OPERATIONS - 2

Deep Water Mooring Systems Using Fiber Ropes

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ABSTRACT

This paper presents an overview of the effort to incorporate fiber ropes in deep water moorings with emphasis in Petrobras' in house developments. It also discusses the experience with the first floating production units to make use of these moorings and the future installations scheduled for 1997, 1998 and 1999.

INTRODUCTION

Drilling and production in water depths exceeding 500 m are a reality in areas such as the Gulf of Mexico, the West of Shetlands and Campos Basin. Today, drilling in these areas is performed by vessels using dynamic positioning systems (DP). It is consensus that floating production is the short/medium term solution for deep water field development.

As an alternative to DP vessels, spread moored semi-submersibles are already being used in water depths down to around 1000 m with pre-deployed lines composed of steel wire rope in the catenary and chain in the ground segment. Floating production systems (FPS) are also being operated for more than five years, offshore Campos Basin, with combined wire rope and chain moorings in similar water depths.

As water depth increases, conventional all-steel spread mooring systems show a number of disadvantages: lower restoring efficiency, a high proportion of tether strength is consumed by the vertical components of line tension, reduced pay-load of the vessel, large mooring radius and sea-floor footprint.

Fiber ropes offer interesting alternatives for these problems. However, incorporating fiber ropes poses a challenge to designers since the non-linear time dependent behavior of these components reflects in the behavior of the moored units in an interactive way [1].

¹ Petrobras R&D

Typical offset limits of floating production units are 10% of the water depth, for the intact system, and 20 % with one line broken. To stick to these limits, there is no need to use high modulus fiber ropes. Actually, taut leg and catenary mooring systems based on high efficiency polyester (PET) fiber rope are very attractive means of mooring deep water rigs [1]. Reduced offset, wave frequency tensions, and vertical component of mooring line tensions are obtained. Taut leg systems greatly reduce sea floor footprint as an additional advantage.

The choice of PET fiber ropes for these applications is based in the following characteristics:

- intermediate modulus;
- low creep;
- good creep rupture resistance;
- good fatigue performance;
- low sensitivity to alternate tension compression;
- low hysteresis;
- very low rate of hydrolysis; and,
- moderate cost.

Applications where high wave frequency strains dominate, suggest the choice of a lower modulus fiber, for example nylon. On the other hand, systems that require very low offsets should benefit from a higher modulus fiber.

Over the past few years several research activities were directed to develop the knowledge and experience to use fiber ropes in deep water moorings. In 1989 a study led by Reading University and Global Maritime, in the UK, identified the most interesting materials for spread and vertical mooring systems [2]. This study already indicated the advantages of using PET fiber ropes in spread moorings. A more complete appraisal of fiber ropes for deep water moorings was presented by Del Vecchio in 1992 [3] and briefly reported in the OTC-92 by Chaplin and Del Vecchio [1].

A number of joint industry projects were conducted and are under way in the UK and in Norway to further advance the use of fiber ropes. Possibly the strongest cooperative effort to built standards for the use of fiber ropes is the JIP "Engineers Design Guide for Deep Water Fiber Moorings" [4].

Along with these JIPs, individual companies with a strong interest in deepwater also developed their own effort. Shell for example, deployed a PET rope as part of an auxiliary mooring for supply boats in 1000 m of water [5]. This system operated successfully for over two years. Other companies as Saga and Statoil are also conducting field trials of fiber moorings.

Subsequent sections of this paper discuss Petrobras' effort to implement the use of fiber ropes in deep water moorings.

R&D PROJECTS

Use of Polyester Ropes in MODU Moorings

The objectives of this project were:

- to qualify two constructions of high efficiency PET ropes for mobile offshore drilling units (MODU);
- develop and test installation and recovery procedures for these ropes; and,
- evaluate the durability of these ropes by means of a long term field test.

This project is now finished. Based on a Minimum Breaking Load (MBL) of 3925 kN (400 metric tones), the construction and manufacturers selected were:

- a parallel strand construction, Marlow Ropes' "Superline"; and,
- a wire rope construction (seven strand) from Phillystran United Ropes.

Both ropes had PET overbraid, for improved handling.

The most important outcomes of this project were:

- a technical specification for high performance polyester fiber ropes to be used in deep water moorings:
- procedures for handling high performance polyester fiber ropes: and,
- the two ropes selected have survived a two years installation on Early Production Systems.

The technical specification, which has become the basis of the specification for FPS, does not directly selects rope construction or diameter. However, in order to guarantee a high tensile efficiency, good fatigue endurance and adequate stiffness, the specification requires:

- a MBL of 3925 kN, corroborated by the testing of three samples to destruction;
- a polyester yarn with a minimum tenacity of 0.78 N/tex;
- a rope core, i.e. the actual load carrying element, with a minimum tenacity of 0.44 N/tex;
- a dynamic stiffness between 8 and 15 N/tex;
- a polyester braided cover with a minimum thickness of 7 mm.

It was concluded that;

- high efficiency polyester fiber ropes provide attractive solutions for MODUs in water depth higher than 500 m;
- hysteretic heating is not an important issue for these ropes in this application, for environments where cycling between 10 and 30% of MBL can be considered a relevant representation of an extreme condition;
- the installation of these ropes requires special handling care such that: the rope is properly coiled on the winch drum, the rope does not bear, under high tension against

sharp corners and does not touch the sea floor or stays in the touch down point for a long period of time; and,

 the use of these ropes in combination with Vertical Loads Anchors (VLAs) seems to be the ideal mooring system for deep water MODUs.

PROCAP 2000

PROCAP 2000 is PETROBRAS' strategic program to develop technology to produce deep water fields. To cope with the future requirements for deep water moorings, PETROBRAS has started a sub-program, within the framework of PROCAP 2000, to develop mooring systems for depths down to 3000 m. The sub-program consists of 5 projects which address:

- 1. catenary spread moorings without buoys;
- 2. taut leg systems;
- 3. taut systems incorporating submersible buoys;
- 4. differential compliance systems (Figure 1); and,
- 5. an expert system to give field support to installations of moorings.

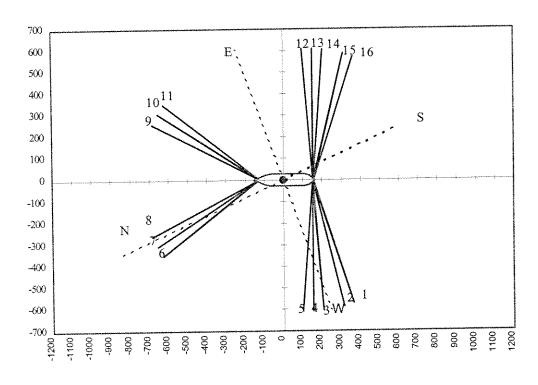


Figure 1 - Sketch of Differential Compliance Mooring System

Except for the taut system with submersible buoys (#3), all projects have already started.

For each alternative mooring system (#1 to #4) the study will address: material properties, design procedures, installation (including workboat) and maintenance.

As far as material properties are concerned these projects will:

- further evaluate polyester fiber ropes load-extension characteristics relevant to changes in draft of taut leg moored ships;
- evaluate the effect of minimum tension on the fatigue endurance of polyester fiber ropes;
- evaluate load-extension characteristics of high efficiency nylon ropes;
- participate in the development of improved termination systems (in house and with rope makers); and,
- evaluate the corrosion resistance of steel wire rope in deep water.

Figure 2 shows an example of force-time graph obtained in the laboratory for a 400 metric tones breaking load rope undergoing an increase in elongation corresponding to a change in draft foreseen in a prospective application of a floating production storage offloading unit (FPSO).

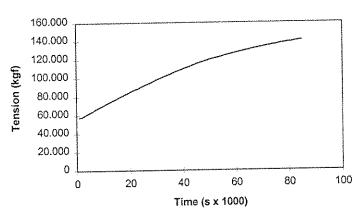


Figure 2 - Laboratory Simulation of Change in Draft in a FPSO

Design procedures and analyses will:

- develop methodologies and provide guidance relevant to each mooring systems by means of: joint industry projects, contracted and in house development;
- generate and analyze results from model scale tests;
- perform parametric analyses of semi-submersibles and ships from 30,000 to 280000 DWT in water depths to 3000 m, for each applicable mooring system; and,
- to develop methodologies to analyze fixed point systems.

Installation will be addressed by means of:

- analysis and sea trail of installation an pre-installation procedures for all the systems;
- development of tools and improved ropes; and,
- specification of mooring lines installation vessels.

As an example of development related to installation, laboratory and field tests are addressing the damage caused by laying polyester ropes on the sea floor. Presently short samples of 400 metric tones breaking load ropes are being subject to tests in an hyperbaric chamber. Initially the samples are taken to pressures of 100 bar, then for various periods of time the rope is put in contact with soil from Campos Basin. When pressure is removed, the amount and extension of ingress of soil particles in the cross section is evaluated optically. The same rope has been deployed and dragged on the sea floor in water depth of 800 m. Testing of this samples include tensioning to 80% of MBL, optical examination and fatigue testing.

As far as Inspection and Maintenance are concerned, the projects will:

- investigate and develop inspection tools for fiber and steel ropes;
- establish criteria for sampling and removal of individual components of mooring lines; and,
- develop procedures for line replacement.

For example, inspection, sampling and discard criteria have already been agreed for the mooring lines of P-19.

INSTALLATIONS UNDER WAY INCORPORATING POLYESTER ROPES

FPSO-II

Installed in 1400 m of water, the mooring system of FPSO-II is a six line catenary system using polyester fiber rope. This system incorporates the high efficiency of the polyester ropes and the compliance in hook up and changes in draft of the catenary system. Each leg is composed of: 1100 m of chain, 600m of 6-strand steel wire rope, 1350 m of PET rope and 120 m of chain in the top segment.

The PET rope in each line is composed of two segments, the lower one being smaller than the water depth, making it safer to pre-deploy. Final hook up is in the connection between the two polyester segments. This ship is a pre-pilot for Marlim South field.

The only problem connected to the performance of the PET ropes, observed during the installation of FPSO-II, was in maintaining the right position of the splice in relation to the thimble, in slack conditions that happened during hook up. This has caused the splice to jump from the thimble and bear against the arms of the joining shackle.

P-34

Installed in 835 m of water, the mooring system of p-34 is a six line catenary system using polyester fiber rope. This system was originally designed with all components in

steel. each leg was designed with 1000 m of chain, 900m of steel spiral strand and 55 m of chain in the top segment.

During deployment a series of torsional problems caused severe damage in the steel spiral. The decision was to redesign the system replacing the full length of spiral strand by 970m of 6970 kN MBL PET fiber rope.

At the time this paper was written four of the six lines had been hooked up successfully.

P-13

P-13 is an 8 line rig already operating as an Early Production System, in 620 m water depth, in Campos Basin. The present mooring system consists of upper segments of six-strand steel wire rope and grounding chain leading to drag embedment anchors. The new system will be taut leg with polyester rope and vertical load anchor. Only a short length (150 m) of the wire rope will remain.

The fiber rope is a parallel strand consisting of seven 12-strand braided cores enclosed in a braided cover. The termination is with eye splices, protected by a circular thimble. Minimum breaking load is 4840 kN (493 metric tones). The rope has been manufactured by Cordoaria São Leopoldo and delivered. Bureau Veritas, the Classification Society of P-13, witnessed the manufacturing and testing of the ropes.

Having decided to use VLAs, the development and purchase of these anchors went on much slower than expected. Two test campaigns, offshore Campos Basin, were performed on Bruce's Denla and one on Vryhof's' Stevmanta anchors.

The prototype Denla had a weight of 1200 kgf. In the first test, it was difficult to embed the anchor. Only one out of five runs was successful. However the anchor showed an uplift capacity in excess of 120 metric tones. A number of modifications were discussed with the manufacturer. In the second test campaign, there were no problems embedding the anchor. In addition to that the anchor was perfected so that: it could be deployed using a single anchor handling boat and also embedded in one direction and used in a different direction.

The prototype Stevmanta, weighting 1800 kgf, was easier to embed and performed well in the first test. However, it seems that this prototype required high tension to embed, compared to the vertical capacity.

The anchors for P-13 are required to withstand a transient dynamic load of 3000 kN and both Vryhof and Bruce were considered ready to supply. However, since no VLA of this size was tested, the winner of the bid for P-13 was required to supply a full size prototype for final approval, before manufacturing all the anchors. Tests on this prototype have been performed and the anchors are being manufactured incorporating further

improvements based on this later test. Once the anchors are delivered to Petrobras, the installation of the taut leg system of P-13 will be scheduled.

P-19 and P-26

For the Marlim Field, two Floating Production Systems based on semi-submersibles, P-19 and P-26, are in the end of their conversion. Table 1 shows the main characteristics of the mooring systems of these rigs.

Table 1 - Characteristics of P-19 and P-26

Rig	P-19	P-26
water depth	770 m	1000 m
overall length	102.1 m	92 m
beam	70.1 m	64.2 m
draft	22.0 m	19 m
displacement	35900 metric tones	38500 metric tones
design code	API RP-2SK	API RP-2SK / DNV POOSMOOR
classification society	Bureau Veritas	DNV
number of lines	16	16
upper component	76 mm RQ4 chain	76 mm RQ4 chain
intermediate component	6970 kN PET fiber rope	6970 kN PET fiber rope
lower component	95 mm RQ3 chain	95 mm RQ3 chain
fixed point	suction anchor	suction anchor
hook up schedule	Sept./97	Aug./97

At the time this paper was written the mooring lines were being pre-deployed. This operation includes suctioning of the anchors, with the lower chain segment and the PET rope connected. The piles are grouped in four clusters. Lines are installed in pairs, one on each cluster, and provisionally hooked up to a two buoy hanger arrangement. The whole operation is proceeding slower than expected, since delays in its start drove the operations into the windiest season in Campos Basin.

IMODCO 3 MONOBUOY

This is another catenary system using polyester ropes. It is scheduled to be installed in 830 m water depth in Marlim field later this year. Each leg is composed of: 900 m of chain, 900 m of 6-strand steel wire rope, 900 m of PET rope and 55 m of chain in the top segment.

The PET rope in each line is composed of two segments, again the lower one being smaller than the water depth. This terminal will off-load the production of P-26.

P-27

This semi-submersible will be installed in 520 m water depth in an extension of Marlim Field. It will have a taut leg system. Although it is a new production system its fixed point system shall be a VLA. Each leg is composed of: 90 m of steel wire rope, 700 m of PET rope and 350 m of chain in the top segment. The system is scheduled to be installed in the first quarter of 1998.

INSTALLATIONS UNDER EVALUATION

New systems with fiber rope are being evaluated both for MODUs and for production units. Availability and cost of DP rigs and safety of operation in areas with many production units are the main drives to use moored drilling/workover rigs in deep water. Table 2 shows the future needs of MODUs for Campos Basin.

Table 2 - MODUs Planned for Campos Basin

Water Depth (m)	Field	Mooring System	Number of Systems
750	Bijupirá Salema	taut leg	2
1200	Marlim South	all steel catenary	1
1200	Marlim South	taut leg	1
1200	Espadarte/Bijupira	taut leg	2
1900	Roncador	taut leg	1

A number of installations of production units are scheduled for 1998 and 1999. Table 3 shows the units incorporating PET ropes being evaluated.

Table 3 - Production Units under Evaluation

Unit	Field	Mooring	Water Depth	No. of Lines	Fixed Point
P-36	Roncador	taut leg	1400	16	suction anchors
P-40	Marlim South	taut leg	1100	20	suction anchors
P-45	Bijupira Salema	DICAS	670	16	HHP anchors

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Composites Technology Used Onshore With Synergy to Offshore Applications J.G. Williams, Composites Engineering and Applications Center, University of Houston and S.A. Silverman, Consultant

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Abstract

The use of Fiberglass Reinforced Plastic (FRP) composites on offshore platforms is rapidly growing, particularly for low pressure piping and secondary structure such as grating. Onshore, FRP pipe systems have been used for over thirty-five years with overall good experiences. In recent years most esearch and development activity in composites in the oilfield has been directed toward offshore applications. Some of this technology also has the potential to improve the profitability and safety of onshore operations. With this in mind, the Composites Engineering and Applications Center recently conducted a study to review the status of FRP technology and consider how corrosion-resistant composite products could better be utilized in onshore petroleum production operations. Applications considered included line pipe, tubing, casing, tanks and vessels, and sucker rods. New products such as spoolable pipe and other emerging technologies were also reviewed for possible onshore applications. Two applications which appear to offer opportunity to use FRP pipe include replacing aging infrastructure in mature waterflood fields and the use of FRP pipe for carbon dioxide injection in enhanced recovery projects. Several advancements made in recent years are discussed in the paper including advanced resin formulations which provide improved damage tolerance and chemical and fire resistance. Good experiences recorded in the study encourages economic incentive for oil companies to increase their utilization of FRP products in onshore oil and gas production operations. Life cycle cost savings of up to 70 percent, for example, have been recorded for some applications using FRP pipe

Introduction

Composite structures are resistant to corrosion and their high pecific strength and stiffness permit them to be designed to

carry load with significantly less weight than similarly designed metal components. When corrosion is a serious issue for metals, composites can often provide reliable long term service at reduced cost. Fiberglass reinforced plastic (FRP) piping systems have been used in onshore operation for over thirty-five years. The largest growth period for FRP products in the United States was during the late 1960's through the early 1980's when U.S. oil companies began large salt water injection projects and corrosion resistant FRP pipe in 3 in. and 4 in. sizes were used for injection lines. FRP products were later qualified for use in large carbon dioxide projects which further expanded the application of FRP pipe. FRP pipe has also been used for flow lines and downhole as casing and tubing. A brief bibliography of the history of onshore applications of FRP products is contained in references 1-15.

The study validated that there are thousands of miles of FRP pipe and other composite products serving successfully throughout the world. United States domestic use of FRP line pipe and tubing is estimated at about \$60 million per year compared to a total market of \$200 million worldwide. The emphasis of many of the major oil companies has shifted away from domestic onshore developments toward deepwater and international projects. However, recent advancements and affordability of 3D seismic and horizontal drilling technology are providing new opportunities for profitable onshore oil and gas development in the United States which could create a demand for more FRP products. Additionally, there is continued expansion of carbon dioxide injection in tertiary recovery projects, particularly in the West Texas area, which could increase the use of FRP products. These two activities along with the replacement of aging infrastructure in mature waterflood fields are seen as the major drivers for growth in the use of FRP pipe onshore in the United States. Recent low oil prices, however, have delayed many development projects.

Good experiences with FRP products provide strong economic incentive for oil companies to increase their utilization in onshore oil and gas production operations. The material cost of FRP pipe and other products are usually more expensive than carbon steel but are less expensive than corrosion resistant alloys. The cost differential narrows when installed costs are compared and usually shifts in favor of FRP when

life cycle costs are considered. Life cycle cost savings of up to 70 percent, for example, have been recorded for FRP pipe. It is the purpose of this paper to provide an update on current composite technology and to highlight the capabilities and life cycle economic benefits of using FRP products in onshore petroleum production operations.

Current FRP Application Experience

One of the approaches to obtain information for this report was to interview oil companies, FRP product manufacturers, and engineering & construction firms to review their experiences and determine their current needs. In addition a questionnaire was circulated to obtain more detailed information. Additional information was gathered from the literature. Presented below is a summary of current applications and field experiences with FRP products.

FRP Line Pipe. The survey indicated the highest utilization of FRP pipe is small diameter low pressure pipe used in water flood service. High-pressure applications are mostly water transfer lines or injection lines less than 6 inches in diameter. A review of some of the experiences recorded in the literature is summarized below.

Brouwer¹⁶ conducted a thorough review of non-metallic piping materials in oilfield use by the Royal Dutch Shell. Shell has over 1395 miles (2250 km or 7.4 million ft) of FRP piping materials in service in over 524 projects around the world. Most applications are 2, 4 and 6 inch diameters with lesign pressures from 10 to 25 bar, however, there has been a shift in recent years to use larger sizes in the 8 inch to 16 inch diameter range. Recently, Shell installed 28 miles (45 km) of 12 to 20 inch diameter pipe involving 3750 adhesive bonded joints with zero leaks following the installation.

Figure 1 taken from reference 16 shows the available operating range for carbon steel, carbon steel with thermoplastic liners, and FRP in use by Royal Dutch Shell. Also shown is the expected operating range for SSL-FRP (steel strip laminate FRP) described later in this report. The operating envelope of carbon steel with liners is approximately equivalent to the envelope of carbon steel. In 1993, experience with liners was limited to 20 inches or less and HDPE was commonly used for the liner material. HDPE has a limiting operating temperature of 104°F (40°C) or 149°F (65°C) depending on the service (hydrocarbon vs. salt water). The introduction of PA and PVDF liners raises the allowable temperature to approximately 176/194°F (80/90° C) or 266°F (130°C), respectively.

R. Franco¹⁷ summarized Exxon's experience with piping for produced water applications. The table below lists common engineering materials used for produced water applications and their estimated service life.

MATERIAL	YEARS IN SERVICE	ESTIMATED LIFE*
FRP Pipe HDPE Lining	15(successful) 15(successful)	20
Cement Lining	20(leaking joints)	25 20 with repairs
Shop Applied Co Downhole Type Flexible Type Bare Steel	Many (with leaks) 3 (successful) Many (with leaks)	10-12

* Time onset of significant maintenance costs when replacement is needed.

Reasons Given For FPR Pipe Failures. Most failures of FRP pipe are due to mechanical damage or improper installation practices. Franco¹⁷ categorizes the main causes of failures of FRP pipe as the following:

- 1. Rough handling.
- 2. Improper make-up procedure.
- 3. Inadequate support of above ground piping.
- 4. Inadequate installation.
- Steel pin in FRP box thread leaks associated with lower hoop modulus of elasticity of the FRP box.
- 6. Soil erosion leading to poor pipe support.

Chemical degradation was deemed not to be a major factor in failures. Unlined aromatic epoxy pipe has given 25 years of life for flowlines in sour oil brine rod pumped wells. UV degradation has been observed on above-ground piping, but is normally limited to a thin layer near the surface and does not appear to cause any significant strength degradation.

One major oil company operating in the Rocky Mountain area encountered problems on an installation of FRP pipes. Problems occurred on a 16 inch trunkline of adhesively bonded FRP line pipe. The ends of the pipe were shaved prior to bonding and left exposed to sunlight for an extended time. The bonded joints did not develop adequate strength and the line failed the hydrotest. The manufacturer covered the cost of cutting the ends and rejoining each pipe with a butt end and wrap procedure. Despite the initial installation problems, the repaired line has been in gas gathering service with 90% CO₂ for over 10 years with no further operational problems.

Most of the failures reported by the Royal Dutch Shell group 18 have been the result of system design errors or poor installations. The main areas of concern are leaking joints, insufficient support, overstressing pipe during installation and expansion problems. With proper installation and materials selection, a maintenance free life of 20 plus years can be expected.

Erosion Resistance of FRP Systems. FRP product manufacturers currently limit liquid velocity to less than 25

ft/sec for low-pressure applications due to concerns for erosion. Lindheim's study¹⁹ was an effort to quantify erosion and cavitation effects in FRP piping for a number of resin systems compared to 6Mo steel and titanium. FRP pipe generally showed higher erosion rates than 6Mo steel and titanium. The erosion resistance of HD polyethylene and polypropylene was comparable to or better than metals or FRP pipe. The test results ranked the materials the same for erosion by slurry impingement and for cavitation.

The matrix material was the controlling factor governing erosion resistance. Epoxy performed better than vinyl ester or polyester. It was concluded that erosion resistance was improved for materials exhibiting toughness at high strain rates, good fiber matrix adhesion, and a resin rich liner which was well adhered to the structural layer and reinforced with a fine surface veil layer. The laminate should have low porosity and a high volume fraction of fibers well bonded to the matrix.

The U.S. Navy has tested the erosion resistance of 2 inch nominal diameter FRP pipe in flowing seawater compared to 90/10 and 70/30 Cu Ni piping²⁰. No erosion was evident after one year of exposure to seawater flows of 11 and 17 ft/sec and after three months of exposure to seawater at 25 ft/sec. Air saturated seawater jet-impingement produced no erosion damage after 60 days. In comparison, similar tests with both CuNi alloys did show erosion damage. Composite pipe is subject to fouling, but it is much more resistant to chlorination reatments typically used to remove fowling.

Downhole Tubing and Casing. FRP downhole tubing has been available for as long as FRP line pipe, but has not reached the same degree of utilization. There is considerable industry literature indicating that FRP tubing can be handled and made-up using traditional equipment with minor modifications. Information readily available indicates that one can hang FRP in the well, log through it, drill through it, mill it and perform almost all of the operations common to oil and gas wells. FRP tubing is available in both threaded and coupled and integral joint configurations from suppliers who provide line pipe.

The corrosion resistance and light weight properties of FRP tubing make it a good candidate material for corrosive environment applications as brine disposal [CLASS II] wells, completion of wells with corrosive fluids and similar applications. However, FRP tubing has not been successful in claiming a significant portion of the downhole tubing market. Industry acceptance of FRP tubing has not been universally achieved because of the following industry perceptions. One concern is that FRP threads are subject to rapid wear as the result of normal make and break. The perceived field service life of FRP downhole tubing is 5 to 10 years primarily because of pin thread wear. Early applications of FRP tubing experienced failure during retrieval operations as the pipe ended to seize and was unable to take the high torque required to break apart the connections. At least two manufacturers

have developed products with couplings designed to resolve this issue and improved performance is reported from the field.

FRP tubing has been successfully used in the chemical industry in wells up to 10,400 feet deep, with bottom hole temperatures of 240°F. In these CLASS I applications, the tubing is subjected to a well integrity test every 12 months.

FRP pipe has been successfully used in recent years to repair corroded casing²¹. In this application, tubing with minimal collar upset is inserted inside the corroded and leaking steel pipe and smaller diameter tubing is placed inside the larger diameter FRP casing.

Practical problems cited with running, handling and operating with FRP tubulars and casing include: (1) lack of consistency in dimensions and pressure ratings between vendors, (2) finding qualified personnel to install product, (3) obtaining proper running tools (i.e., elevator slips, BOP rams crushing FRP joints), (4) fishing parted tubing or casing, and (5) perforating poorly cemented casing which shatters the FRP pipe.

Sucker Rods. Only one of the eight oil companies interviewed uses FRP sucker rods routinely and estimates 10-15% of their rod purchases are FRP products. The FRP rods are used primarily to unload gear-box torque on high fluid level wells and high water volume wells. Pump-off controllers are always placed on wells with FRP rods to ensure that the rods do not go into compression. The average well depth is 6000 feet with a maximum depth of 10,000 feet. In addition to the benefit of increased production, corrosion inhibition efficiency is easier to achieve in wells with lower fluid levels. Many wells with high fluid levels often develop holes in the casing due to poor distribution of corrosion inhibitor and exposure to corrosive fluids.

FRP Sucker Rod Experience. Ghiselin²² showed that FRP sucker rods offer distinct economic advantages under certain well conditions. Wells with high fluid levels could often produce more oil if the fluid levels were reduced. This condition is also an indication that the equipment is operating at capacity. High fluid level conditions can also result in ineffective corrosion inhibition and rod failures. For new installations, use of FRP rods that are 70% lighter than steel can result in the use of a smaller motor and gearbox and less power usage. FRP rods can be dynamically tuned to provide more stroke and pumping efficiency than steel rods. The lower coefficient of friction of FRP also generally results in less tubing wear.

Ghiselin²² presented data from three wells in the Clearfork unit in Andrews County, TX, producing from 6000 feet with high fluid levels and equipment overloads. Mixed strings of FRP rods and steel rods (placed on the bottom to keep the string in tension and absorb compressive forces near the

pump) were run in all three wells. The net effects were that the total fluid production increased 28%, oil production rose by 46.7 bpd (60.8%) with an average reduction in power consumption of 20% per barrels fluid lifted per day. The fluid levels were reduced an average of 949 feet simplifying corrosion treatment. Annual increased profitability for the three wells was \$255,683 with a recovery of cost in 54 days. If all of the remaining wells in the field were converted, it was estimated a net profit gain of about \$1 million could be achieved per year.

Taylor²³ describes the use of FRP sucker rods in a deep, 12,500 feet, West Texas well. Lease expenses dropped 82% after the installation of an FRP /steel rod string. Previously, the well used a power oil jet pump system. The rod string design consisted of 6188 feet of 1.25 inch FRP rods (50%), 2725 ft of 7/8 inch steel rods, and 3500 ft of 3/4 inch steel rods. The fiberglass rod loading was 53% of the allowable maximum stress and pump plunger travel increased from 156 to 196 inch at the pumped-off condition. Lease expenses dropped from \$7500/month to \$1350/month. The system cost of \$100,000 was paid back in 1.4 years. The economic limit of the well was lowered from 450 barrels of oil per month to 64 barrels oil per month, thereby increasing recoverable reserves by 190,000 barrels.

Carbon Ribbon Sucker Rod. The carbon ribbon sucker rod, developed for Amoco, 24 in the configuration of a spoolable tape with dimensions of 1.45 inch by 0.212 inch can be wound onto a six inch wide 10-foot diameter reel, and is designed to be used in combination with steel rods at the bottom of the well. The carbon based rod was conceived as a system that could be used to increase production rates to levels previously unobtainable, due to high stress loading in steel rods and limited fatigue life in fiberglass rods. Because of the light weight and flexibility, it conforms to well-bore deviations with less rod/tubing friction than steel rods and should reduce loading and improve energy efficiency for pumping units.

The fatigue life of the carbon ribbon rod material is superior to that of steel. At 10 million cycles, carbon fiber composites survive working at 60% of their ultimate strength, while steel operates at 40% and fiberglass operates at only 20% of ultimate tensile strength. The product is made from Thornel T-300, 12K carbon fiber tow with a vinyl ester resin. Kevlar® fibers are added to the edges of the rod to improve toughness and damage resistance. The product can be made in continuous 3000-foot lengths by a pultrusion process.

Tanks and Vessels. Use of FRP tanks onshore is declining among major oil companies due to a concern regarding safety for use of FRP tanks with hydrocarbons. In particular, there is concern regarding the susceptibility of FRP tanks to lightning strikes. Several companies indicated they are phasing out the 1se of FRP tanks due to the apparent concern about lightning strikes and fires. A review of the use of tanks and vessels

offshore is presented in reference 25-27.

Some oil companies purchases FRP tanks which meet the API 12P specification. FRP tanks as large as 750 barrels are used for water storage. They are also used for pit enclosures, sumps, and chemical tanks. One oil company uses FRP tanks of 500 barrels or less for salt water service and another oil company estimates that 50% of their tank purchases in 1997 were FRP. These tanks are one-piece filament wound and rated for atmospheric service only. No hydrocarbons are allowed due to concern for lightning strike.

Several methods have been devised to address the lightning strike issue. Horizontal lightning rods are installed 20-30 feet above the tanks. Another approach is to install a stainless steel tubing in the tank running it to the bottom of the tank through a packoff assembly at the top. The stainless steel tubing is then attached to a buried grounding rod. Some manufacturers are incorporating carbon fiber or carbon black into the laminate or resin to make the tank walls more conductive.

FRP tanks are used offshore for storage of diesel, lube oil, and water. Fire tests conducted on FRP and metal storage tanks containing hydrocarbons²⁸ indicate an FRP tank performs better in a fire than steel or aluminum tanks. The conductive properties of metal allow the fluid to heat rapidly and vaporize. Steel tanks can rupture and aluminum tanks can melt if fire continues for an extended period of time. Fires involving metal tanks are difficult to extinguish because leaking gas reignites on hot metal surfaces. The contents of the FRP tanks stayed cooler (due to lower thermal conductivity) and FRP tanks remained leak free considerably longer in a hydrocarbon pool fire.

New FRP Products and Emerging Applications

Several new products are under development or have been introduced recently by manufacturers of FRP products. This technology is relatively new and is reported herein for information and no endorsement of specific products is implied or intended. Some of these new products are initially targeted for offshore petroleum applications or the chemical industry, but could also provide cost effective benefits for onshore petroleum production operations. In addition, the study identified new application opportunities where composite products could provide enabling capabilities or extend the application operating temperature and pressure ranges.

SSL FRP Piping. High pressure, large diameter piping products called Steel Strip Laminate (SSL) pipe is being developed by Ameron. SSL incorporates spirally-wound, multiple layers of steel sandwiched between layers of fiberglass. Products are being developed in sizes of 8 inch to 40 inch diameter with operating pressures in the range 140-350 bar (2030-5075 psi). The temperature envelope is -40°F to 230°F (-40°C to 110°C). This new product provides the

opportunity to significantly expand the operating range for corrosion-resistant, large-diameter, high-pressure FRP pipe.

Fire Resistant FRP Pipe. Ameron has developed a fire resistant pipe called Bondstrand PSX based on a polysiloxane phenolic resin^{30,31}. The phenolic resole resin system has been modified with polysiloxane to enhance the fire and mechanical performance properties. Bondstrand PSX pipe, fittings and adhesives have been tested and certified by third party laboratories to verify performance against flame spread and heat, smoke and toxic fume generation. These products have received IMO Level 3 fire resistance acceptance by the United State Coast Guard. The system is designed for operating pressures less than 225 psi and is primarily aimed at use in fire water and utility systems where fire resistant piping with low smoke emissions and low toxicity are required. Pipe is available in 1 thru 12 inch and can be made in 14 and 16 inch sizes, if required.

Dual Containment Piping System. Ameron has developed the concept of coaxial pipe and fittings to address the use of FRP pipe for dual containment applications. Mechanical properties of this type of piping system are expected to be better than single wall FRP pipe due to the higher stiffness of the coaxial system. The cost of the coaxial system is expected to be less than a pipe-in-pipe system. The fittings are more compact than traditional pipe in a dual wall system. Impact resistance testing has shown a 400% increase in energy required to cause failure of the pipe.

Chemically Resistant and Damage Tolerant Resins. Smith Fiberglass has introduced a new FRP piping system (Z-CORE) developed with an advanced resin system formulated for aggressive solvent and acid applications including chemicals such as fluorobenzene, dichloroethane, chloroform and 98% sulfuric acid. The pipe is rated for 150 psig and 275°F in sizes 2 inch through 6 inch diameters. Applications for the onshore market might include drilling and workover rigs handling aggressive acids and solvents. Smith Fiberglass has also introduced a new FRP pipe (Cyonyx) based on polydicyclopentadiene (DCPD) resin which is highly resistant to degradation from aggressive chemical and to damage from impact³². Initial tests on the material show it to be extremely resistant to impact damage. Processing is fairly complex; however, if fabrication methods can be developed, the material would have merit for a much broader class of structural configurations.

Spoolable Pipe. There was great interest from all companies surveyed regarding new spoolable composite pipe products for low pressure gathering lines and high pressure water injection lines. A review of spoolable composite products currently available and under development was presented at the Second International Conference on Composite Materials for Offshore Operations. Companies 'eveloping or marketing spoolable composite pipe products aclude: Hydril Company, 33 Compipe AS, 34 Fiberspar

Spoolable Products Inc., 35,36 Proflex Pipe Comporation, 37 and Tubes d'Aquitaine. Hydril is leading a NIST Advanced Technology Project joint venture to develop a broad range of spoolable high performance composite tubing products. The joint venture is a five-year program initiated in 1995. Compipe is developing products for subsea injection lines and flowlines and recently announced a contract to supply 10 miles of spoolable composite pipe for high pressure subsea methanol injection lines for the Asgard field in Norway. Fiberspar's efforts were initially in collaboration with Conoco³⁹ with primary focus on composite coiled tubing, but they have expanded the product line to include other applications including line pipe and production tubing. The Pro-Flex design consists of an inner thermoplastic liner surrounded by multiple independent (unbonded) cylindrical composite structural layers encapsulated in an outer cover. The product is available commercially in 2, 3, and 4-inch diameter sizes. Tubes d'Aquitaine is developing composite pipe products constructed using thermoplastic resin. Royal Dutch Shell conducted field trials in Oman on thermoplastic line pipe made by Tubes d'Aquitaine from polyethylene resin and aramid fiber with reportedly good resutls³⁸.

Spoolable pipe has the potential to be applied onshore for water injection lines, flowlines, and downhole tubing. It is expected that the price of the pipe will be more expensive than conventional FRP pipe, however, the cost of installation should be significantly lower and the corrosion resistance will provide life cycle cost benefits. Elimination of most of the connections reduces a common source for leaks thus providing better reliability. The main limitation with spoolable pipe for onshore applications will be cost and the maximum diameter pipe which can be spooled and transported on roadways.

Cryogenic Fracturing. A new techniques for fracturing downhole formations has been developed based on thermally shocking the formation using liquid nitrogen⁴⁰. The technique uses FRP pipe to transport the liquid nitrogen to moderate depth formations at typical fracturing rates and at cryogenic temperatures (-320°F to -232°F) while protecting the casing from thermal shock damage. At liquid nitrogen temperatures, steel pipe becomes brittle and may fracture. Construction of all stainless steel surface piping, manifolding and wellhead components prevents thermal contraction surface problems and the use of free hanging FRP tubing insulates the casing from thermal shock damage. Glass fibers are not affected by the low temperature and the glass transition temperature of epoxy resins used in making FRP pipe for the oilfield are in excess of 200°F. Therefore, during use, the epoxy polymer is in the glassy state and changes little in brittleness at temperatures below the glass transition temperature whether at room temperature (70°F) or at the temperature of liquid nitrogen (-321°F). FRP pipe has been deployed successfully in field tests as tubing to transport liquid nitrogen downhole.

In-situ Processed Casing and Line Pipe Liners. Composite products are under development which are initially

fabricated in long lengths with an unpolymerized resin and placed on a spool for transport. The products called Casing-Flex and Flextube are installed in a well or pipeline to repair defective casing or line pipe. The tube is pressurized and the resin is cured insitu. The material can be manufactured in 4 inch to 14 inch diameters with lengths of over 3280 feet and reeled on a drum. For monodiameter drilling, very long tubes can be used to replace the casing strings resulting in a substantial decrease in volume drilled. For remedial relining projects, short tubes that can pass through the production tubing can be used to seal off perforations, repair corroded casing or seal off side tracked holes. Casing-Flex can be run with an electric wireline apparatus. This type of technology could also make possible drilling and completing wells with coiled tubing thus eliminating the derrick or draw works.

Higher Temperature and Pressure Capability. A need was identified in the survey for FRP pipe capable of operating at pressures and temperatures higher than currently available. One company requested composite piping for gas flow lines up to 600 psi and crude oil lines up to 1200 psi operating at temperatures approaching 392°F (200°C). Resin systems capable of operating in this temperature range are currently available, but the cost would be significantly higher than currently used epoxies. It remains to be seen if the market for high temperature pipe would support the price required for products.

Super-Critical CO_2 . A need exists for an FRP pipe capable of transporting CO_2 at super-critical temperature and pressure. FRP pipe suppliers have responded and products with alternative resin materials are currently being evaluated in field tests.

Lined Pipe Alternatives. Cement and FRP lined steel are additional choices available to address onshore oilfield corrosion problems. Life expectancy for lined pipe is in excess of ten years. To reduce the cost, used steel tubing in inventory can be rehabilitated by cutting new threads, blast cleaning and adding a lining of cement or FRP.

In addition to traditional alternatives, new liner technologies are becoming available. HDPE liners are installed in standard steel tubes to provide added corrosion resistance. The liner is not normally bonded to the steel and can be subject to explosive decompression if gases permeate the liner and rapid pressure drops are imposed. Steel coiled tubing with a HDPE liner is also being used in some completions

Oilfield Market for FRP Products

The worldwide market for FRP pipe products is estimated at about \$200 million. The total market for FRP pipe in the Western Hemisphere is over \$100 million and may be broken down by regions as follows:

USA Janada \$60 million \$20 million

Mexico	\$5 million
South America	\$25 million

The market is estimated to be divided into the following applications:

Onshore Line Pipe	80%
Offshore Utility Piping	10%
Tubing	10%

The market for line pipe can be further segmented as follows: 25% gas gathering, 25% crude oil gathering (multiphase lines), and 50% salt water injection. The market for FRP downhole tubing represents approximately \$5,000,000 which is only 2.5% of total tubular sales.

Cost Comparison of Common Piping Materials

The alternatives commonly used for corrosive service in onshore oil fields are carbon steel with continuous corrosion inhibition, HDPE lined steel, plastic coated steel, cement lined steel, and type 316SS or duplex SS. Some use of PA (polyamide liners) has recently been reported for higher temperature applications. For low pressure gas gathering service, bare HDPE pipe is used by some operators. Detailed economic calculations to determine life cycle costs must be run on a specific project basis. Figure 2, taken from a report by Brouwer, 16 shows the total installed CAPEX costs for PE liners, PA liners, FRP, and RTP (reinforced thermoplastic pipe). The installed cost of FRP or RTP pipe ranges from cheaper to more expensive than carbon steel pipe. The steel pipe does not include the cost of corrosion inhibitors or life cycle costs. Often the complexity of the piping system will determine the choice of materials based on the number of fittings and the diameter of the pipe.

Conclusions.

This study indicates that currently available FRP pipe products are being utilized in increasing quantities worldwide driven by their corrosion resistant properties and associated cost advantages. High potential also exists for products currently in development to provide new capabilities including improved damage tolerance and increased pressure and temperature operating range. The high cost-savings available should serve as an incentive to the growth of FRP pipe in onshore operations.

The use of FRP pipe for flowlines and injection lines has proven to be cost-effective in onshore operations where corrosion is an issue. The current primary application for FRP line pipe is small diameter lines (less than 6 inch diameter) used for hydrocarbon gathering and water injection distribution operating at less than 2000 psi and at temperatures less than 200°F. There is a growing demand for low pressure lines (< 500 psi) in larger sizes (6 inch to 10 inch) to permit greater through-put of produced fluids in maturing water floods. Although the installed cost of FRP pipe is usually slightly higher than carbon steel pipe, FRP pipe can often

provide significant cost savings (up to 70 percent) based on life cycle costs.

The study identified a need for FRP pipe capable of operating at temperatures approaching 392°F (200°C) with gas pressures up to 600 psi and crude oil lines with pressures up to 1160 psi. Currently available advanced resin materials could be used to serve this need if the improved performance justified the higher cost. Water injection lines are required for pressures up to 3050 psi and supercritical CO₂ service lines are needed for use in WAG applications. Six, eight and ten-inch lines with pressure ratings as high as 5000 psi are needed. One supplier recently introduced a higher-pressure (5400 psi) pipe based on reinforcing fiberglass pipe with circumferentially wound steel strips.

FRP casing and tubing applications have been limited, however, specialty applications such as the use of slimhole FRP casing to repair the casing in old water injection wells have been highly successful. New running techniques and improved hanger/packers have been developed to facilitate this process. API has for several years worked on a specification for fiberglass tubing. It is anticipated that final resolution and publication of this document would help expand the tubing application of FRP pipe. Research conducted by the University of Houston^{42,43,44} could provide the methodology to accurately predict failure under combined loading. It may also be economical in the future to improve the performance of downhole tubing using low cost carbon liber.

FRP sucker rod use appears attractive for some applications with case studies indicating a relatively short time for economic pay-back. Lowering the operating costs can also allow additional reserves to be produced from marginal wells.

Interviews with corrosion engineers in oil companies identified that the potential for lightning strike and fire on fiberglass tanks is a major concern. Tank manufacturers are trying to address the concern by making the tank wall conductive to drain off static charge.

Developments in emerging reelable composite technology and spoolable composite tubing provide the enabling technology for an all composite oil or gas well. The total cost and time required to drill and complete wells could be reduced significantly by eliminating the full-sized drilling rig, the size of the drilling site, the volume drilled and by eliminating the transport of heavy pipe. Drilling of slim hole monodiameter wells using composite coiled tubing rig could reduce drilling costs substantially. Completion of the wells could be performed with coiled tubing equipment using spoolable composite tubing. Small diameter flowlines up to 4-inch could also be installed using spoolable composite pipe.

A barrier to the expanded use of FRP products in U.S. onshore silfields appears to be the lack of adequately trained personnel

to design FRP systems. This, in part, is due to the turnover and downsizing of technical staff in the industry over the last ten years. Younger staff members have very little exposure to composite materials. A training course is needed that would address the practical aspects of design and installation of FRP piping systems targeted for field facilities engineers of the oil companies and design facilities engineers at engineering and construction firms. The Composites Engineering and Applications Center at the University of Houston offered an FRP pipe workshop in the fall of 1998 and plans to offer additional courses in the future. Another training course is needed which would help production technicians and engineers understand how to successfully design and use FRP products in downhole applications including topics such as casing/liner installation for carbon dioxide wells, injection tubing installation, design and use of FRP sucker rods and utilization of new spoolable pipe products.

Acknowledgement

The information reported in this paper drew heavily on a study conducted in 1997 for the Composites Engineering and Applications Center for Petroleum Exploration and Production (CEAC) at the University of Houston to evaluate the opportunities and barriers to the expanded use of FRP products in onshore petroleum production operations. The authors wish to thank the CEAC membership for permission to place this information in the public domain.

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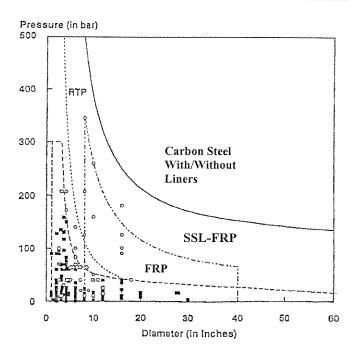


Figure 1. - Operating envelopes of carbon steel, FRP, lined carbon steel pipe, Steel Strip Laminate (SSL-FRP) and Reinforced Thermoplastic Pipe (RTP) pipe systems ¹⁶. (Filled squares - GRE; Open Circles - Lined Carbon Steel)

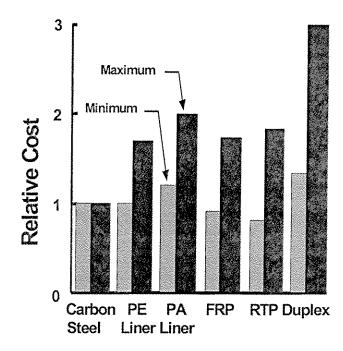


Figure 2. – Installed (CAPEX) costs of pipe relative to carbon steel. 16









CEAC/MMS SEMINAR ON COMPOSITES OFFSHORE

APPENDICES



Gulf of Mexico OCS

Pacific OCS **Contacts** Reading Room <u>Links</u> Conferences & Workshops







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Oil and Gas Development on the OCS in a Low Oil Price Environment

Carolita U. Kallaur, Associate Director, Offshore Minerals Management Remarks to Independent Petroleum Association of America

Good afternoon. It is my pleasure to be here today representing the Minerals Management Service(MMS). I think we all benefit from continuing to have a dialogue on the many important issues facing government and industry today.

I would like to take this opportunity to talk to you about the role of MMS on the Outer Continental Shelf (OCS) and how we look at oil and gas development from the perspective of a regulatory agency. For those of you who are less familiar with MMS and what we do, I will give you a very brief introduction to the OCS Program and the range of legal mandates that guide us. Then I will talk about how MMS is dealing with the issues currently confronting us.

I hope that "WE", collectively, can try to figure out how best to deal with the challenges and opportunities before us. We at MMS do understand the effects that low oil prices have on those of you in the oil and gas industry. The prices we've seen in the last 3 to 4 months have been especially hard hitting. Finding ways to provide some measure of relief to industry without compromising attainment of other objectives is a high priority for us.

We've set up a team to address this issue and will be engaged in a continuing dialogue with you and other constituents while we take a look at the avenues available to us to help maintain a viable industry while meeting government responsibilities and preserving competition.

For more information: As most of you know, MMS has 2 main functions -- to manage mineral extraction on Darryl.Francois@mms.gov the Federal Outer Continental Shelf and to collect mineral revenues for all Federal and Indian lands. We manage 1.5 billion acres of submerged lands on the OCS, from which you and others produce 22 percent of our domestic oil and 27 percent of our domestic natural gas. The Gulf of Mexico OCS has all but about 200 of the almost 8200 active leases on the OCS and accounts for 88 percent of OCS oil production and 99 percent of OCS natural gas production.

> The MMS mandate is subject to a number of laws, including the National Environmental Policy Act (NEPA), the Coastal Zone Management Act (CZMA), the Oil Pollution Act of 1990, the Deep Water Royalty Relief Act, and, of course, the OCS Lands Act. The OCS Lands Act assigns MMS several responsibilities. Among these are:

- to expedite exploration & development of the OCS
- to protect the human, marine, & coastal environments
- to obtain a fair & equitable return for the public on OCS resources, and
- to preserve & maintain competition.

What's important to note is that--unlike the Department of Energy and other agencies with more focused mandates--we're obliged to pursue a very broad range of objectives and to do so under all market conditions. This means that we sometimes are limited in what we can do to assist any specific group of constituents. For example, we cannot seek to implement policies to favor independents over the majors or vice versa. We really seek to maintain a level playing field for all parties concerned.

Before I talk about the issue foremost on your minds, I would like to touch upon some changes we have been making in our regulatory program and some international activities we are pursuing to make sure we influence decisions that will someday affect us all.

MMS recognizes that technological advances alone are not enough to ensure safe operations. As industry continues to come up with innovative ways to develop offshore resources, MMS must also adapt its regulatory program to changing realities. We continue to emphasize to industry the importance of having a systematic approach to safety that stresses the human factor and its interrelationship with safety management systems. We are also tailoring our compliance program so that it focuses on those activities that pose the highest risk. We will inspect those facilities with the greatest risk and pay less attention to the good performers.

We are implementing regulatory changes that reflect our emphasis on performance over process. We will soon be proposing a rule that shifts the responsibility for ensuring that workers are properly trained to the operator, replacing the current requirement that training be carried out at MMS certified schools. We also are entertaining requests for departures from our regulations where a company can assure an equal or higher level of safety and environmental performance.

Additionally, we are updating our regulations to ensure that operators with clear, continual records of poor performance can be disqualified from operating on a facility, operating in a region, or operating on the OCS, and ultimately can be prohibited from acquiring any new leases.

And lastly, we also have developed a more extensive industry recognition program that recognizes, not only companies, but individuals who demonstrate true leadership. Our <u>award ceremony</u> is scheduled for April 16 at the Renaissance Houston Hotel.

The globalization of offshore oil and gas operations has led to additional opportunities for the MMS. As more areas around the world are opened up to oil and gas companies, there is a growing need for us to be aware of the activities of international standard-setting bodies and the regulatory programs of other governments. Our efforts focus on being proactive, not reactive. To this end we have signed memoranda of understanding with China, Australia and, most recently, Norway. We helped organize an international workshop on platform decommissioning with the Asia Pacific Economic Cooperation organization. We also sponsored a forum on international regulatory practices at last year's Offshore Technology Conference. MMS is a member of the International Regulators Forum, which has representation from Canada, Norway, the United Kingdom, the Netherlands, and Australia. We also are involved with the International Committee on Regulatory Authorities Research & Development to share scientific research.

However, of all international work we are involved in today, the one that I believe will have the most impact in the future is that involving international standards. It is our goal that we be able to contribute to sound technical decisions that reflect a careful balancing of sometimes conflicting factors. This is a challenge for industry as well as government, and we are participating in the development of international standards and guidelines through organizations such as the ISO.

Two recent developments bring the importance of this issue to the fore. Last year the <u>Oslo-Paris Commission</u>, which consists of members of the European Union plus Norway, decided to ban disposal of platforms in most instances. This Commission is also taking steps to ban the use of synthetic drilling muds, which may be very important in deepwater operations. While these restrictions apply only to European waters, they become a standard against which we need to defend alternative policies in international bodies such as IMO.

There also is movement in the <u>Commission on Sustainable Development</u>, which is part of the United Nations, to set up a global authority for offshore oil and gas operations. The U.S., both government and industry, needs to be an active participant in these deliberations to ensure that any decisions reached reflect a careful balancing of technical, environmental, and economic factors. MMS, for the first time, has a marker in its fiscal year 2000 budget to reflect the importance of this emerging issue.

As a preamble to our discussion of the current low-price environment, let's briefly look at how the situations facing us--both the industry and MMS--have changed over the last 15 years. In 1982, during the boom years following the overthrow of the Shah of Iran, MMS was created as a bureau of the <u>Department of the Interior</u> and, ultimately, given all OCS management responsibilities. In 1986, the worldwide oil price bust had a devastating effect on the U.S. oil & gas industry; many jobs were lost and economic activities were curtailed. As the situation lingered for years, without any real improvement in external conditions, many of you responded to this challenge by implementing internal changes and becoming more efficient.

Although a gradual recovery in energy prices did provide some incentive to restart U.S. activities, most oil and gas industry capital investment went overseas. This "exodus," combined with declining reserve projections, led to a perception by many that the Gulf of Mexico was a "Dead Sea". In the 1990's many technological advances, especially the onset of powerful computer workstations, widespread use of 3-D seismic, and improvements in horizontal drilling capabilities and subsea completion methods, helped to rejuvenate the industry. Commercial <u>subsalt</u> successes and the discovery of several deepwater elephants, coupled with strengthening oil and gas prices, produced an industry poised to take off. And after passage of the Deep Water Royalty Relief Act in 1995, it did indeed take off.

The period of 1996-1997 was marked by record levels of leasing, exploration, and development activity, particularly in the <u>deepwater Gulf of Mexico</u>. But here we are today, once again facing devastatingly low oil prices. The drop in prices, beginning in 1998 and most noticeable in the past 3-4 months, has begun to take its toll on industry activity, especially in shallow water.

As regulators, we cannot let some objectives be compromised because of low prices or other hardships faced by our constituents, and we have to keep a long-term perspective. I trust we all agree that it never makes good business sense to compromise on safety and environmental protection. Clearly, we all suffer if someone has a major accident. Public confidence is undermined, and restrictive polices are more likely to be put in place. There are other issues where it is less clear. Companies compete for leases with specified terms and conditions to include such things as royalty rates and diligence requirements. Particularly in periods of low prices, there is interest by some parties in relaxing some of these requirements.

In regulating the industry, we try to assure that there is a level playing field, so we have to be very careful about providing benefits to one set of constituents in a way that harms others, including the public. Outside of the deepwater Gulf of Mexico, we have procedures to consider royalty relief for capital projects and end-of-life properties. Although we must assure a fair return to the public for its resources, our bottom-line criterion is that we want to avoid losing production. We think if this condition is met, relief is much more easily defended.

Relaxing diligence requirements is another issue because, in the end, we may be rewarding those who delayed activity even though requirements were known up front. At the same time, we don't want to foreclose discussion of the issues.

While we are considering a range of possible policy or other changes, there are a few actions that we either are implementing or expect to implement soon. First, for the Gulf of Mexico, we are considering granting lessees one additional year before they have to remove platforms after production ceases. This extension would expire a year from issuance. Lessees, we hope, will have a somewhat better economic climate by then to finance abandonment costs. We have issued new economic assumptions for obtaining royalty relief in the deepwater of the Gulf of Mexico. The economic assumptions update those that were issued in November 1998 and that were increasingly out of line with the current price of oil. We are also issuing revisions to the MMS guidance for royalty relief, including conditions for applying for relief outside of established programs. Both of these Notices to Lessees are on the MMS homepage

In addition, we are working with the <u>Department of Energy to take royalty in kind in the Gulf of Mexico</u> and use the oil we collect to fill the Strategic Petroleum Reserve. This allows the Government to use this opportunity to rebuild SPR inventories during a period when oil prices are at historic lows. In regard to actions we're taking,

proposals we just made public, other changes we're considering--and even changes we don't now consider promising, we want to hear from you. Although many of our objectives are not open for reconsideration, we are completely open to suggestions as to how to achieve those objectives.

For example, we have indicated that we will not compromise on safety and environmental protection, and that is true. However, even here, we are willing to consider ways to make our regulations more efficient and grant departures where satisfactory alternative measures are proposed. In the end, our major contribution may not be a specific set of policies but rather a continuing commitment to improve the efficiency of government and the regulations under which you operate.

As we move into the next century, to remain the best minerals manager possible, our focus must be to continue to be aware of the latest advances in scientific research technology and regulatory approaches. Our commitment to a high level of environmental and safety performance must never waiver. We recognize that a serious offshore accident can undermine public confidence in the program. And, in all things, we must continue to engage our stakeholders in a dialogue that seeks to incorporate best practices and benefit from the widest range of experiences possible.

Our objective is to ensure that our Nation receives fair market value from offshore leases through a well administered leasing program and regulatory measures that optimize performance. We must be aware of international developments and how they may affect our U.S. operations through cooperative relationships with other regulators, and be a part of standards development efforts within international organizations. By doing this, we will help to promote a healthy offshore industry that provides needed energy and security benefits for our Nation.

Memorandum of Understanding
Between
Minerals Management Service
U.S. Department of the Interior
and
United States Coast Guard
U.S. Department of Transportation

Ia. Purpose

This Memorandum of Understanding (MOU) defines the responsibilities of the Minerals Management Service (MMS) and the United States Coast Guard (USCG) relating to managing the activities of MODU's, fixed, and floating systems. It is designed to minimize duplication and promote consistent regulation of facilities under the jurisdiction of both agencies. This MOU does not apply to deepwater ports as licensed by the Secretary of Transportation under the Deepwater Port Act of 1974, as amended.

Ib. Scope

This MOU covers oil and gas activities located in the Outer Continental Shelf (OCS). However, oil-spill preparedness is for facilities located seaward of the coast line, unless noted otherwise. Certificates of financial responsibility are for certain facilities located in the OCS and the State waters included in the definition of Covered Offshore Facility found at 30 CFR 253.3. An MOU, dated February 3, 1994, among the Departments of Transportation and the Interior and the Environmental Protection Agency established jurisdictional responsibilities for facilities located both seaward and landward of the coast line.

II. Definitions

For purposes of this MOU, the following definitions apply:

Act - The OCS Lands Act (OCSLA) -- 43 U.S.C. 1331 et seq.

<u>Coast Line</u> - The line of ordinary low water along that portion of the coast that is in direct contact with the open sea and the line marking the seaward limit of inland waters, as defined by the Submerged Lands Act (43 U.S.C. 1301 (c)).

Outer Continental Shelf – The submerged lands that are subject to the Act.

OCS Activity - Any activity in the OCS associated with exploration, development, production, transporting, or processing of OCS mineral resources including but not limited to oil and gas.

OCS Facility - Any artificial island, installation, pipeline, or other device permanently or temporarily attached to the seabed, erected for the purpose of exploring for, developing, producing, and transporting resources from the OCS. This term does not include ships or vessels for transporting produced hydrocarbons. The following are types of OCS facilities:

- 1. <u>Fixed OCS Facility</u> A bottom-founded OCS facility permanently attached to the seabed or subsoil of the OCS, including platforms, guyed towers, articulated gravity platforms, and other structures. This definition also includes gravel and ice islands and caisson-retained islands engaged in OCS activities used for drilling, production, or both.
- 2. <u>Floating OCS Facility</u> A buoyant OCS facility securely and substantially moored so that it cannot be moved without a special effort. This term includes tension leg platforms, spars, semisubmersibles and shipshape hulls.
- 3. <u>Mobile Offshore Drilling Units</u> (MODU's) Vessels capable of engaging in drilling operations for exploring or exploiting subsea oil, gas, or mineral resources.

OPA - The Oil Pollution Act of 1990 (Pub. L. 101-380).

Regional Director (RD) - The MMS officer delegated the responsibility and authority for a region within MMS. The USCG referrals for violations occurring in a particular MMS Region would be made to that MMS Region's RD.

Regional Supervisor (RS)- The MMS officer (or the authorized representative) in charge of operations within a Region.

<u>Vessel</u> - Every description of watercraft or other artificial contrivance used, or capable of being used, as a means of transportation on the water. This term does not include atmospheric or pressure vessels used for containing liquids or gases.

<u>Violation</u> - Failure to comply with the OCSLA, any regulations, or the terms or provisions of leases, licenses, permits, or rights-of-way issued under the OCSLA.

III. Responsibilities

The following table lists the lead agency for system responsibilities associated with MODU's and fixed and floating OCS facilities. Other agency roles are identified where applicable. The lead agency is responsible for coordinating with the other agency as appropriate. The attachments to the table list the typical equipment that is included in the system.

The MMS and USCG will work together to develop the standards necessary to implement this MOU. Where the agencies have overlapping responsibilities, they will work together to minimize duplication.

				Lead Agency	÷.	
Item	System	Sub-system	MODU	Fixed	Floating	Other Agency Role / Comments
_	Design & Operating Overview/Plan				Womanian International Control of the Control of th	
1.3		Deepwater Operating Plan	N/A	MMS	MMS	Where required
1.b		Design Basis Document	nsce	N/A	OSCG	
1.c		Design, fabrication, and installation verification plans	N/A	MMS	MMS	Section applies to MMS's Certified Verification Agent (CVA) Program.
7	Structural Integrity					
2.a		Structural integrity, modifications for construction and repair requirements	nsce	MMS	MMS & USCG	USCG responsibilities for fabrication, installation, and inspection of floating units are found in 33 CFR Subchapter N. MMS responsibilities are found in 30 CFR Subpart I. USCG and MMS will each review the design of the turret and turret/hull interface structure for ship-shape floating facilities. All other aspects of the design and fabrication of all ship-shape floating facilities will receive only USCG review. All design, fabrication, and installation activities of all non-shipshape floating facilities will be reviewed by both agencies.
2.b		Design environmental conditions	nsce	MIMS	MMS	Establishes in-place design environmental criteria.
		1 TO THE PARTY OF			DSCC	Establishes design environmental criteria for intact and damage stability.
2.c		Risers (drilling, production, and pipeline)	MMS	MMS	MMS	Some pipeline risers may be subject to the Research and Special Programs Administration's (RSPA) jurisdiction.
3	Floating Stability		nsce	N/A	nsce	USCG reviews and approves stability and sends copies to MMS.
4	Station Keeping					
4.a		Foundations	USCG	MMS	MMS	
4.b		Mooring and tethering systems	nsce	MMS	USCG & MMS	USCG is not responsible for site specific mooring analyses
j. 4		Dynamic positioning	nsce	N/A	DOSO	
	With the second				Andrews of the second s	



				Lead Agency	*	
	Cretory	Sub-system	MODU	Fixed	Floating	Other Agency Role / Comments
14.b		Drilling systems	DOSO	MMS	DSCC	See Attachment A for definition of Drilling Systems.
					MMS *	* MMS is the lead agency for drilling equipment installed for a finite time and designed for removal
14.0		Emergency lighting power generation and distribution	nsce	DOSO	nsce	
14.d		Hazardous areas classification	nsce	MMS	MMS and USCG	MMS and USCG will work on common, logical standards to minimize duplication of effort for industry.
15	Aids to Navigation		nsce	usce	nsce	
16	Communications		nsce	OSCC	nsce	
17	Pollution Prevention					
17.a		Pollution not associated with vessel transfers	nsce	osce	nsce	Garbage and plastics per the International Convention for the Prevention of Pollution from Ships MARPOL 73/78
			MMS	MMS	MMS	Other Pollution
17.b		Petroleum and other product transfers to and from a vessel (includes lightering of produced hydrocarbons)	nscg	nsce	nsce	
18	Cranes and Material Handling Equipment					
18.2		Crane design, certification, and operations	nsce	MMS	nsce	
18.b		Other Material Handling Equip.	nsce	MMS	nsce	
19	Ventilation		And the second s	and Assessment (1) to receive the second sec	A A A A A A A A A A A A A A A A A A A	
19.а		Accommodations and machinery spaces	nsce	nsce	nsce	
ARRAM CONTRACTOR OF THE PROPERTY OF THE PROPER	And the second s	The state of the s				

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Attachment A

Drilling, Completion, Well Servicing and Workover Systems

System requirements for operating the following equipment and systems:

- Drilling, production, and workover risers
- Blowout prevention equipment and control systems
- Drilling system and related relief valves, vent system, pressure vessels and piping, pumps, water systems, safety systems, cementing systems, and circulating systems
- Riser and guideline tensioning systems
- Motion compensation systems
- Instruments and controls
- Atmospheric vessels and piping
- Fitness of the Drilling Unit
- Lifting and hoisting equipment associated with the derrick
- Cementing systems
- Circulating systems, including: pipes and pumps for mud; shale shakers; desanders; degassers.
- Structures including derrick and sub-structure
- Bulk material storage and handling systems
- Other pressurized systems designed for industrial operations

Attachment B Production Systems

Includes but not limited to the following equipment:

- Hydraulic systems
- Connections between production and workover (industrial) systems
- Production safety systems including subsurface and surface well control
- Relief valves, relief headers, vent and flare systems
- Production wells and wellhead
- Well-handling equipment (contract drilling rig)
- Instrumentation, controls, and measurement (including oil and gas)s
- Gas compression
- Process system and related pumps
- Odorization for gas piped into enclosures
- Process system and related pressure vessels and piping
- Process system and related heat exchangers, including waste heat recovery units
- Chemical injection and treatment systems

Attachment C Fire Protection, Detection and Extinguishing

Includes the following equipment:

- Deluge systems in the wellbay area
- Firewater pumps, piping, hose reel and monitor equipment
- Foam extinguishing equipment
- Fixed gaseous extinguishing equipment [carbon dioxide(CO2) and halon alternatives]
- Fixed watermist extinguishing equipment
- Portable and semi-portable extinguishers
- Fire and smoke detection (excludes interfaces to MMS regulated safety systems)

IV. Civil Penalties

The USCG reports violations of OCSLA statutes or regulations that may result in civil penalty action to MMS. The USCG will investigate and document OCSLA based violation cases according to the procedures in 33 CFR 140.40 with the following clarification:

- 1. The cognizant Officer-in-Charge, Marine Inspection (OCMI) makes the determination whether a violation "constitutes or constituted a threat of serious, irreparable, or immediate harm." If the OCMI determines:
 - a. That it does, then the OCMI will refer the case to MMS and recommend that a civil penalty be assessed.
 - b. That it does not, then the OCMI will establish a reasonable time for the violator to fix the problem. The OCMI may do this in consultation with MMS, particularly on matters in which MMS has expertise or knowledge of industry practice. If the violator does not correct the problem, or does not file an appeal with the appropriate USCG official in the allotted time, the OCMI will refer the case to MMS, pursuant to 43 USC 1348 (a).

When referring a case to MMS, the OCMI will forward the following information:

- i. The case file, which consists of a summary of the investigation and a USCG determination of the regulations violated.
- ii. A description of the seriousness of violation and any incidents actually associated with the violation.
- iii. If requested, additional information concerning the merits of a civil penalty action. All physical evidence remains with the USCG, but available to MMS upon request.
- 2. If the violator files an appeal of a USCG's enforcement action the USCG will not forward the case to MMS until the appeal has been resolved.
- 3. Upon receipt of the violation report, the MMS Regional Civil Penalty Coordinator will appoint a Reviewing Officer (RO) who will process the report in accordance with the MMS OCS Criminal/Civil Penalties Program Guidebook.
- 4. Notification of the MMS RO's decision regarding the civil penalty assessment, collection, compromise, or dismissal shall be provided to the OCMI originating the violation report.

V. Oil Pollution Responsibilities

A. Certificates of Financial Responsibility (COFR)

- 1. The MMS issues certifications of oil-spill financial responsibility for certain facilities located in the OCS and State waters included in the definition of Covered Offshore Facility found at 30 CFR 253.3. The COFR ensures that responsible parties can pay for cleanup and damages from facility oil spills.
- 2. The MMS will provide COFR-related information to the USCG upon request. Upon request from the USCG, MMS will provide available information for any covered OCS facility (COF) in certain OCS and the State waters included in the definition of Covered Offshore Facility found at 30 CFR 253.3 that are involved in an oil pollution incident including:
 - (1) Copies of the lease, permit, or right of use and easement for the area in which the COF is located;
 - (2) Contacts for claims;
 - (3) Agents for service of process;
 - (4) Amounts guaranteed; and
 - (5) List of all responsible parties.
- 3. The USCG issues COFR for vessels and floating OCS facilities which store oil. This COFR is in addition to the MMS COFR and addresses the operator's financial responsibility for the clean up and damages from oil discharges resulting from non-well-related sources and produced oil stored onboard the floating OCS facility.

B. Oil Spill Preparedness and Response Planning

- 1. The MMS, for all facilities seaward of the coast line, requires that responsible parties maintain approved Oil Spill Response Plans (OSRP) consistent with the area contingency plan; ensures that response personnel receive training; and that response equipment is inspected. The MMS will require unannounced oil-spill response drills. The MMS RS will advise the Federal On Scene Coordinator (FOSC) of drills to coordinate participation, and avoid conflict or duplication.
- 2. The USCG Captain of the Port serves as the pre-designated FOSC in accordance with the National Contingency Plan. The appropriate FOSC will also jointly approve OSRPs for floating facilities which store oil. Participation in MMS drills will be at the discretion of the FOSC. The FOSC will advise the MMS RS of spill-response drills and activities, such as exercise and response activities, occurring on facilities seaward of the coast line.

C. Spill Response

- 1. All spills are required to be reported to the National Response Center (NRC). The NRC provides notification to the appropriate agencies and State offices. Additionally, OCS facility owners or operators are required to report spills of one barrel or more to the MMS RS.
- 2. The FOSC will direct and monitor Federal, State, and private actions, consult with responsible parties, and determine the removal action. The MMS RS will direct measures to abate sources of pollution from an OCS facility. However, if a discharge poses a serious threat to public health, welfare, or the environment, in accordance with Public Law 101-380 (OPA) Sec. 4201, the FOSC may mitigate or prevent the substantial threat of a discharge and notify the MMS RS as soon as possible. The MMS will authorize the return of an OCS facility to operation in coordination with the FOSC.

VI. Exchanging Services and Personnel

To the extent its own operations and resources permit, each agency will provide the other agency with assistance, technical advice, and support, including transportation, if requested in accordance with 43 U.S.C. 1348. Exchange of services and personnel is non-reimbursable (except for pollution removal funding authorizations for incident specific fund access). The assistance may extend to areas beyond the OCS where one Agency's expertise will benefit the other agency in applying and enforcing its safety regulations.

VII. Other Cooperative Functions

- 1. Both agencies will exchange data and study results, participate in research and development projects, and exchange early drafts of rulemaking notices to avoid duplicative or conflicting requirements.
- 2. Both agencies will review current standards, regulations, and directives and will propose revisions to them as necessary in keeping with the provisions of this MOU.
- 3. Both agencies will review reporting and data collection requirements imposed on operators of OCS facilities and, where feasible, eliminate or minimize duplicate reporting and data collection requirements.
- 4. Each agency will conduct scheduled and unannounced inspections to ensure compliance with its own requirements. If the inspector notices deficiencies that fall within the responsibility of the other agency, the deficiency will be reported to the other agency for action. However, if the deficiency may cause serious or irreparable harm to persons, property, or the environment, the inspector may take the necessary preventative action. The preventative action will then be reported to the other agency.

VIII. Accident Investigations

The MMS or the USCG is responsible for conducting investigations and preparing a public report for each major fire, oil spillage, serious injury, and fatality associated with OCS activities. To avoid duplication of effort and to simplify administration, the responsibility for investigating and preparing a public report for these incidents rests with the agency that is listed in Section III as being responsible for the system associated with the incident. In addition, the MMS investigates blowouts and the USCG investigates collisions.

For those incidents for which both agencies have an investigative interest in the system associated with the incident, one agency will assume lead investigative responsibility with supporting participation by the other agency. The lead agency in a joint investigative effort shall investigate and prepare, approve, and release the report in accordance with the normal procedures of that agency, subject to the following terms and conditions:

- 1. The lead agency shall be determined through mutual agreement. If mutual agreement is not reached, each agency may decide to conduct its own investigation.
- 2. The specific details of a supporting agency's participation in a joint investigation shall be determined on a case-by-case basis through mutual agreement.
- 3. Prior to the public release of a joint agency report, the supporting agency will be afforded an opportunity to comment on the report. If the supporting agency's conclusions and/or recommendations differ with those of the lead agency, either both conclusions and/or recommendations will be included in the lead agency's report in a mutually acceptable manner, or a joint report will not be issued, and each agency may issue separate reports.

IX. Implementing this MOU

- 1. Each agency will review its internal procedures and, where appropriate, will revise them to accommodate the provisions of this MOU. Each agency will also designate in writing one senior official who will be responsible for coordinating and implementing the provisions of this MOU.
- 2. Each agency will designate regional officials to be responsible for coordinating and implementing the provisions of this MOU in their respective regions.
- 3. The USCG--MMS MOU concerning regulation of activities and facilities in the OCS, dated August 29, 1989 is canceled on the effective date of this agreement.
- 4. If new technology (or new uses of current technology) require a change to this MOU, the MMS regional office and appropriate USCG district will work together to reach an agreement. The MMS regional office and the USCG district will notify their respective Headquarters office

of any change. If the MMS regional office and the USCG district office can't reach an agreement, it will be elevated to MMS and USCG Headquarters. The new policy will become part of a revised MOU the next time the MOU is revised.

X. Savings Provision

Nothing in this MOU alters, amends, or affects in any way the statutory authority of MMS or the USCG.

XI. Effective Date

This MOU is effective upon signature.

XII. Termination

Both parties may amend this MOU by mutual agreement and either agency may terminate it with a 30-day written notice.

Signed at Washington, D.C., December 16, 1998.

Oommandant,

U.S. Coast Guard

Department of Transportation

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Minerals Management Service, Department of the Interior



Memorandum

Subject:

From:

POLICY FILE MEMORANDUM ON THE FIRE PERFORMANCE REQUIREMENTS FOR PLASTIC PIPE PER IMO RESOLUTION A.753(18)

Chief, Office of Design and Engineering Standards

Date: 2 8 MAY 1998

PFM 1-98 16714

Reply to Attn. of: G-MSE-4

C.S. Myskowski

202-267-0169

To: Distribution

- 1. PURPOSE: This Policy File Memorandum (PFM) provides guidance on the fire test requirements for type approval of plastic pipes for use on ships as set forth in IMO Resolution A.753(18), Guidelines for the Application of Plastic Pipes on Ships, and as required by 46 CFR 56.60-25(a). This PFM also provides guidance on fire test requirements for plastic piping for use in specific locations unique to offshore oil platforms.
- 2. APPLICABILITY: This Policy File Memorandum addresses the fire performance of plastic piping for use on inspected vessels, including mobile offshore drilling units (MODUs) and floating production platforms. It is not intended to eliminate any other design criteria or requirements pertaining to the material, construction, or performance of the plastic piping in the non-fire condition, nor is it intended to be applied retroactively to applications that have previously received approval on a case-by-case basis. The MODUs and floating production platforms affected by this PFM include all those subject to the MODU regulations per 46 CFR, Subchapter I-A and/or the IMO Code for the Construction and Equipment of Mobile Offshore Drilling Units, 1989.
- 3. BACKGROUND: The International Maritime Organization (IMO), recognizing that there is an increasing interest within the marine industry to use materials other than steel for pipes and that there were no specific requirements for plastic pipes in the existing international regulations, adopted Resolution A.753(18) on 4 November, 1993, Guidelines for the Application of Plastic Pipes on Ships. Subsequently, the Coast Guard adopted the IMO Guidelines as an option to the existing federal regulations on nonmetallic piping materials in 46 CFR 56.60-25. In application of these Guidelines to actual test procedures and data, the Coast Guard has determined that there are certain areas which need further consideration and clarification.
- 4. **DISCUSSION:** This policy file memorandum addresses qualification and testing of piping for fire endurance, flame spread, smoke, and toxicity. The guidelines given in enclosures (1) and (2) are intended to clarify and supplement IMO Resolution A.753(18).

SUBJ: POLICY FILE MEMORANDUM ON THE FIRE PERFORMANCE REQUIREMENTS FOR PLASTIC PIPE PER IMO RESOLUTION A.753(18)

Enclosure (1) provides information of a general nature with respect to the fire testing and type approval of plastic piping per IMO Resolution A.753(18). Enclosure (2) provides information specific to certain MODUs and floating production platforms and allows deviation from A.753(18) based on their unique layout and operating conditions.

5. ACTION:

- 5.1 The enclosed guidelines shall be used for the testing and approval of plastic piping, fittings and joints intended for use on inspected vessels, including MODUs and floating production platforms, in accordance with 46 CFR 56.60-25(a) and IMO Resolution A.753(18).
- 5.2 Questions arising which pertain to specific issues not addressed in this policy should be referred to the Commandant (G-MSE-4), U.S. Coast Guard Headquarters, 2100 Second St., S.W., Washington, DC 20593-0001.

MARK G. VANHAVERBEKE CAPTAIN, US COAST GUARD

Dist: G-MSE

MSC

G-MOC

G-MSE-3

G-MSO

G-MSE-4

- Encl: (1) Guidelines on the Fire Testing Requirements for Plastic Pipe per IMO Resolution A.753(18)
 - (2) Guidelines on the Fire Endurance Requirements for Plastic Pipe for Use on Mobile Offshore Drilling Units and Floating Production Platforms

1 General

1.1 As part of the Coast Guard's ongoing harmonization of federal regulations with international safety standards, IMO Resolution A.753(18) was adopted into Title 46 of the Code of Federal Regulations, Subchapter F, on September 30, 1997. In application of IMO Resolution A.753(18) to actual test procedures and data, the Coast Guard has determined that there are certain areas which need further consideration and clarification. These guidelines are intended to accomplish this need in the area of fire performance testing and type approval of plastic pipe.

2 Testing Laboratories

- 2.1 The laboratory conducting the testing discussed below shall be an accepted independent laboratory in accordance with 46 CFR 159.010. In addition, when conducting the flame spread, smoke and toxicity tests detailed in these guidelines, the laboratory must be in compliance with IMO Resolution MSC.61(67), The International Code for Application of Fire Test Procedures (FTP Code).
- 2.2 The results of fire endurance testing conducted by a laboratory not in compliance with section 2.1 above may be used in an application for approval under these guidelines if:
- 2.2.1 the testing was conducted prior to the promulgation of these guidelines; and,
- 2.2.2 it is demonstrated that the testing laboratory would have complied with the requirements of 46 CFR 159.010-3 at the time the testing was conducted.

3 Piping Material Systems

- 3.1 All fire endurance, flame spread, smoke, and toxicity testing, where required, shall be conducted on each piping material system.
- 3.2 Changes in either the type, amount, and/or architecture, of either the reinforcement materials, resin matrix, liners, coatings, or manufacturing processes shall require separate testing in accordance with the requirements of IMO Resolution A.753(18) and of these guidelines.

4 Fire Protective Coatings^v

- 4.1 Where a fire protective coating is necessary for achieving either the fire endurance, flame spread, or smoke and toxicity criteria, the following requirements apply:
- **4.1.1** Pipes shall be delivered from the manufacturer with the protective coating on, in which case on-site application of protection would be limited to what is necessary for installation purposes (e.g. joints). Alternatively, pipes may be coated onsite in accordance with the approved procedure for each combination, using the approved materials of both pipes and insulation, subject to onsite inspection and verification.
- **4.1.2** The liquid-absorption properties of the coating and piping should be considered. The fire protection properties (e.g. fire endurance, flame spread, smoke production, etc.) of the coating should not be diminished when exposed to salt water, oil or bilge slops.
- 4.1.3 Fire protective properties of coatings should not degrade due to environmental effects over time, such as ultraviolet rays, exposure to salt water, temperature and humidity. Other areas to consider are thermal expansion, resistance against vibrations, and elasticity.
- 4.1.4 The adhesion qualities of the coating should be such that the coating does not flake, chip, or powder when subjected to an adhesion test.
- 4.1.5 The fire protective coating should be resistant to impact.

5 Level 3 Fire Endurance

- 5.1 In order to demonstrate compliance with Appendix 2, Test method for fire endurance testing of water-filled plastic piping (Level 3), of IMO Resolution A.753(18), the following additional procedures should be followed:
- **5.1.1** All typical joints and fittings intended to be used shall be tested. Elbows and bends need not be tested provided the same adhesive or method of joining utilized in straight piping tests will be used in the actual application.
- 5.1.2 Qualification of piping systems of sizes different than those tested shall be allowed as provided for in Table 5.1.2 below. This applies to all pipe, fittings, system joints (including joints between non-metal and metal pipes and fittings), methods of joining, and any internal or external liners, coverings and coatings required to comply with the

^{*}Because there are currently no widely accepted standards for fire protective coatings as applied to plastic piping, the Commandant(G-MSE-4) will evaluate test data and information and determine the acceptability of such testing and information on a case-by-case basis.

performance criteria.

- 5.1.3 No alterations to couplings, fittings, joints, fasteners, insulation, or other components shall be made after the commencement of the fire endurance testing(e.g. flange bolts shall not be re-torqued after completion of the fire exposure testing, prior to hydrostatic testing; post fire hydrostatic testing shall be conducted without altering the component in any way).
- 5.1.4 The acceptance criteria shall be as specified in IMO Resolution A.753(18), Appendix 2. In the case of deluge and sprinkler system piping required to meet the Level 3 requirements, these criteria need not be met provided the testing and design procedures set forth in Appendix A of these guidelines are followed. Appendix B of these guidelines provides an example of the additional reporting requirements if the alternative acceptance criteria are utilized. Sprinkler and deluge system piping required to meet Level 1 or Level 2 fire endurance requirements must meet the acceptance criteria per IMO Resolution A.753(18), Appendix 1.

Table 5.1.2, Qualification of Piping Systems of Sizes Different than Tested

mm	Minimum Size* Approved,	Maximum Size* Approved,
0 to ≤50	Size Tested	mm
>50 to ≤152	Size Tested	Size Tested
>152 to ≤300		≤152
>300 to ≤600	Size Tested	≤300
****	Size Tested	≤600
>600 to ≤900	Size Tested	<u></u> ≤900
>900 to ≤1200	Size Tested	~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
ze refers to the actual of	utside diameter of piping.	≤1200

6 Flame Spread

- 6.1 All pipes, except those fitted on open decks and within tanks, cofferdams, void spaces, pipe tunnels and ducts, should have low flame spread characteristics as determined by test procedures given in IMO Resolution A.653(16), Recommendation on Improved Fire Test Procedures for Surface Flammability of Bulkhead, Ceiling and Deck Finish Materials, and as modified for pipes in Appendix 3 of IMO Resolution A.753(18).
- 6.2 When conducting flame spread testing of plastic piping in accordance with Appendix 3 of IMO Resolution A.753(18), testing need not be conducted on every pipe size. Testing should be conducted on piping sizes with the maximum and minimum wall thickness intended to be used. This will qualify all piping sizes for a specific piping material, provided that the wall thickness falls within the tested range.

6.3 The test specimens need not be wrapped in aluminum foil as required in section 8.1.1 of IMO Resolution A.653(16).

7 Smoke and Toxicity Test Requirements

- 7.1 Piping systems meeting the smoke and toxicity classification criteria specified in Annex 1, Part 2 Smoke and Toxicity Test, of IMO Resolution MSC.61(67), may be installed in concealed or inaccessible spaces in accommodation, service spaces and control stations and need not meet the additional requirements in 46 CFR 56.60-25(a)(2).
- 7.2 When smoke and/or toxicity testing is conducted, the following shall be required:
- 7.2.1 The test shall be conducted in accordance with Annex 1, Part 2 Smoke and Toxicity Test, of IMO Resolution MSC.61(67) with the following modifications:
- 7.2.2 Testing should be conducted on piping sizes with the maximum and minimum wall thicknesses intended to be used. This will qualify all piping sizes for a specific piping material, provided that the wall thickness falls within the tested range.
- 7.2.3 The test sample should be fabricated by cutting pipes lengthwise into individual sections and then assembling the sections into a test sample as representative as possible of a flat surface. All cuts should be made normal to the pipe wall.
- 7.2.4 The number of sections that must be assembled together to form a square test sample with sides measuring 75mm, should be that which corresponds to the nearest integral number of sections which will result in a test sample with an equivalent linearized surface width between 75mm and 90mm. The surface width is defined as the measured sum of the outer circumference of the assembled pipe sections normal to the lengthwise sections.
- 7.2.5 The assembled test sample should have no gaps between individual sections.
- 7.2.6 The assembled test sample should be constructed in such a way that the edges of two adjacent sections should coincide with the centerline of the test holder.
- 7.2.7 The test samples should be mounted on calcium silicate board and held in place by the edges of the test frame and, if necessary, by wire.
- 7.2.8 The individual pipe sections should be mounted so that the highest point of the exposed surface is in the same plane as the exposed flat surface of a normal surface.

- **7.2.9** The space between the concave unexposed surface of the test sample and the surface of the calcium silicate backing board should be left void.
- 7.2.10 The void space between the top of the exposed test surface and the bottom edge of the sample holder frame should be filled with a high temperature insulating wool where the pipe extends under the frame.
- 7.2.11 When the pipes are to include fireproofing or coatings, the composite structure consisting of the segmented pipe wall and fire proofing shall be tested and the thickness of the fireproofing should be the minimum thickness specified for the intended usage.
- 7.2.12 The test sample should be oriented in the apparatus such that the pilot burner flame will be normal to the lengthwise piping sections.

8 Information Required

- 8.1 In addition to the information required by the various standards referenced in this policy, the following information shall be provided to Commandant (G-MSE-4), 2100 Second St., S.W., Washington, DC 20593-0001:
- 8.1.1 a test report containing the information required by 46 CFR 159.005-11
- 8.1.2 maximum allowable working pressure of piping;
- 8.1.3 piping sizes to be approved;
- 8.1.4 locations and applications that approval is requested for;
- 8.1.5 all piping system joints and fittings to be approved;
- 8.1.6 piping system adhesives to be approved; and,
- 8.1.7 the installation procedures manual.

APPENDIX A: ALTERNATIVE ACCEPTANCE CRITERIA FOR SPRINKLER AND DELUGE SYSTEM PIPING REQUIRED TO MEET LEVEL 3 FIRE ENDURANCE TESTING PER A.753(18), APPENDIX 2

TESTING

- 1. During the test, no leakage from the sample(s) should occur except that slight weeping through the pipe wall may be accepted.
- 2. After termination of the burner regulation test, the test sample, together with fire protective coating, if any, should be allowed to cool to ambient temperature and then hydrostatically tested to the rated pressure of the pipe(s) as defined in paragraphs 2.1.2.2 and 2.1.3.2 of IMO Resolution A.753(18). Where practicable, the hydrostatic test should be conducted on bare pipe; i.e. pipe which has had all of its coverings, including fire protection insulation, removed, so that leakage will be readily apparent.
- 3. The pressure should be held for a minimum of 15 minutes and the average leakage rate per minute and the pressure shall be recorded.
- 4. From this information, a leak rate factor (LRF) shall be derived for each pipe section, fitting or joint in the following manner:

For pipe sections with no joints or fittings

$$LRF_{LP} = \frac{Q_{avg}}{1.4\sqrt{P_{mawp}}}$$

and for joints and fittings

$$LRF_{f} = \frac{Q_{avg}}{\sqrt{P_{mawp}}}$$

where

 LRF_{LP} is the Leak Rate Factor for pipe sections per linear foot of pipe, LRF_J is the Leak Rate Factor for joints and fittings, Q_{avg} is the average 15 minute leakage rate at the rated pressure in gpm, and P_{maxp} is the hydrostatic pressure during the test in psig.

5. From the leak rate factors, "K" factors and "K/L" factors shall be determined for the size range of pipe sections, joints, and fittings that may be qualified per section 5 of these guidelines, in the following manner:

For pipe sections with no joints or fittings

$$K/L = \frac{D_{actual}}{D_{test}} LRF_{LP}$$

and for joints and fittings

$$K_{J} = \frac{D_{actual}}{D_{test}} LRF_{J}$$

where

K/L is the "K/L" factor for pipe (gpm/psig^{1/2}/ft).

 K_J is the "K" factor for each joint type (gpm/psig^{1/2}),,

 D_{actual} is the inside diameter (inches) of pipe size for which a "K" factor is desired, and D_{test} is the inside diameter (inches) of the pipe subjected to the level 3 fire endurance test.

6. The "K" and "K/L" factors for pipe sections, fittings, and joints for the range of pipe sizes for which type approval is granted shall be listed on the type approval certificate.

HYDRAULIC DESIGN PROCEDURES

1. In the hydraulic design of a sprinkler system or deluge system, the following procedures shall be followed:

The system shall be designed per NFPA 13, NFPA 15, or another recognized industry standard applicable to the system, assuming no leakage from joints, fittings or pipe sections.

Virtual sprinkler heads shall be added (as discussed below) to account for the expected leakage rate from the pipe sections, joints and fittings. The hydraulic calculations for the system shall be re-calculated to ensure that the system will operate normally under the increased water demand. This can be verified by ensuring that the hydraulically most remote nozzle will operate at the minimum required pressure and flow rate when the virtual sprinkler heads are included in the calculations. A check should be made to ensure that the maximum working pressure of the sprinkler or deluge nozzles, pipes and fittings will not be exceeded when no leakage from the piping system occurs.

The increased flow rate required for a system when the virtual sprinklers are added to the hydraulic calculations shall not exceed 110 % of the flow rate required for the system without the addition of the virtual sprinkler heads.

2. Virtual sprinkler heads shall be added as follows:

For each straight section of piping of a given diameter, a virtual sprinkler head shall be added at the mid-point of the pipe section. The "K" factor of the virtual sprinkler head shall be calculated as the product of the length of pipe and the "K/L" factor listed on the type approval.

For each joint or fitting for a given pipe diameter, a virtual sprinkler head shall be added at the location of the joint. The "K" factor of the virtual sprinkler head shall be as listed on the type approval certificate.

For deluge system piping, virtual sprinkler heads shall be added for all plastic piping downstream of the water supply valve.

For sprinkler system piping, with fusible heads, virtual sprinkler heads shall be added for all plastic piping located only in the hydraulically most remote required area of sprinkler operation.

APPENDIX B: EXAMPLE OF LEAKAGE RATE DATA REPORTING

Company: ABC FRP MFG

Pipe Tested: Iceman, 2" Nominal Pipe Size (3 tests)

Summary: Three IMO level 3 fire endurance tests were performed to qualify pipe sizes from 2" up to 6" per section 4.2 of the guidelines. Test 1 was conducted on a straight section of pipe only. Test 2 was conducted on the permanent joint type. Test 3 was conducted on the flanged joint type. The results of the hydrostatic pressure tests are listed below. During the fire endurance tests, no leakage was noted from any of the samples. Measured Data:

Pressure Test (MAWP): 250 psig

Leak Rate (straight pipe): 0.5 gpm (Test 1) Leak Rate (permanent joint): 1.0 gpm (Test 2) Leak Rate (flanged coupling): 1.5 gpm (Test 3)

Calculated Data:

LRF_{LP} (straight pipe): 0.0226 LRF_J (permanent joint): 0.0632 LRF_J (flanged coupling): 0.0949

PIPE QUALIFIED BASED ON TESTS ABOVE

Nominal	Pipe Section/Joint	Inside	D _{actual} /D _{test}	K/L Factor	K Factor
Pipe Size,		Diameter,		(straight	(joints)
In.		In.		pipe)	
2	straight pipe	2.067	1.0	0.0226	
	permanent joint		1.0	-	0.0632
	flanged coupling		1.0	-	0.0949
2.5	straight pipe	2.469	1.19	0.0269	-
	permanent joint		1.19	-	0.0752
	flanged coupling		1.19	-	0.1129
3	straight pipe	3.068	1.48	0.0334	**
	permanent joint		1.48	_	0.0935
	flanged coupling		1.48	-	0.1404
3.5	straight pipe	3.548	1.72	0.0389	**
	permanent joint		1.72		0.1087
	flanged coupling		1.72	••	0.1632
4	straight pipe	4.026	1.95	0.0441	<u> </u>
	permanent joint		1.95	-	0.1232
	flanged coupling		1.95	-	0.1851
5	straight pipe	5.047	2.44	0.0551	-
	permanent joint		2.44	+	0.1542
	flanged coupling		2.44	-	0.2316

GUIDELINES ON THE FIRE ENDURANCE REQUIREMENTS FOR PLASTIC PIPE FOR USE ON MOBILE OFFSHORE DRILLING UNITS AND FLOATING PRODUCTION PLATFORMS

1 General

- 1.1 IMO Resolution A.753(18) was developed and intended primarily for seagoing ships. These policy guidelines are intended to allow deviation from IMO Resolution A.753(18) based on the unique layout and operating conditions found on mobile offshore drilling units (MODUs) and floating production platforms. Deviations from IMO Resolution A.753(18) have previously been allowed on a case-by-case basis in certain fire main system and deluge system plastic piping applications. These guidelines have been developed as a result of several successful applications as well as extensive fire testing conducted by the Coast Guard, foreign regulatory agencies, and manufacturers of plastic pipe.
- 1.2 The fire endurance requirements matrix, Appendix 4 of IMO Resolution A.753(18) does not adequately address the application and location of certain plastic fire main and deluge piping systems. These guidelines are intended to supplement IMO Resolution A.753(18) in the areas where it is lacking and are intended to be entirely consistent with the IMO document. Therefore, the expanded use of plastic piping on MODUs and floating production platforms is permitted subject to the limitations and testing requirements discussed below. During plan review, the Marine Safety Center (MSC) has the authority to determine the extent and application of these guidelines. The replacement of existing steel or metallic piping with plastic piping on existing MODUs and floating production platforms will require prior review and approval by the Officer in Charge of Marine Inspection (OCMI).

2 Definitions

Deluge System: A piping system employing open nozzles attached to a piping system connected to a water supply through a valve that is opened by the operation of a detection system installed in the same areas as the nozzles. When this valve opens, water flows into the piping system and discharges from all nozzles attached thereto.

Open Deck: A deck which is completely exposed to the weather from above and from at least two sides.

Semi-enclosed Location: A location where natural conditions of ventilation are notably different from those on open decks due to the presence of structures such as roofs, windbreaks, and bulkheads, and which are so arranged that the dispersion of gas may not occur.

GUIDELINES ON THE FIRE ENDURANCE REQUIREMENTS FOR PLASTIC PIPE FOR USE ON MOBILE OFFSHORE DRILLING UNITS AND FLOATING PRODUCTION PLATFORMS

3 Fire Main

- 3.1 Plastic fire main system piping installed on offshore floating drilling and production platforms may meet the Level 3 fire endurance requirements as specified in IMO Resolution A.753(18), in lieu of the Level 1 or Level 2 requirements specified in IMO Resolution A.753(18), Appendix 4, when the below conditions are satisfied. In all other cases, plastic fire main system piping shall meet the fire endurance requirements specified in A.753(18), Appendix 4.
- 3.1.1 Plastic piping must be located on the exterior perimeter of the platform and shielded by primary structural members from potential sources of fire which may occur on or emanate from the platform.
- **3.1.2** Plastic piping must be located so that pooling of flammable liquids below the piping is not possible.
- 3.1.3 The fire main system design shall be such that the plastic sections are continuously maintained in the wet condition.
- 3.1.4 The fire main shall be equipped with an adequate number of isolation and cut-off valves such that, if a section of the system were to fail, it could be isolated and the remainder of the system would remain capable of supplying fire water.

4 Deluge System

- 4.1 Deluge piping systems installed on offshore floating drilling and production platforms shall meet the fire endurance requirements for water spray systems as specified for various locations in IMO Resolution A.753(18), Appendix 4. Deviation from these requirements will be allowed for piping installed in open deck or semi-enclosed locations provided the piping and the piping system satisfy the requirements specified in sections 4.1.1 through 4.1.8 below.
- **4.1.1** The deluge system piping must meet the Level 3 fire endurance requirements as specified in IMO Resolution A.753(18) and further clarified in Enclosure (1) of PFM 1-98.
- 4.1.2 In addition to meeting the Level 3 fire endurance requirements, the deluge system piping must meet the requirements of the wet/dry fire endurance testing specified in section 4.9 below. Other wet/dry fire endurance test methods that may be equivalent to or more severe than the methods described herein will be considered on a case-by-case

basis. Other methods that have been accepted as of the date of this policy are described in the Appendix to these guidelines.

- **4.1.3** An automatic fire detection system shall be installed in areas protected by the deluge system.
- **4.1.4** The deluge system shall be designed to activate automatically, with <u>no</u> human action necessary to set it into operation, upon detection by the automatic fire detection system.
- **4.1.5** Each section or area served by a deluge system should be capable of being isolated by one water supply valve only. The stop valve in each section should be readily accessible and its location should be clearly and permanently indicated.
- **4.1.6** Means should be provided for preventing the water supply valves from being operated by an unauthorized person.
- **4.1.7** The design of the deluge system shall be such that upon fire detection, the time required to have water flowing through the hydraulically most remote nozzle shall be less than one minute. This shall be verified by system testing at the time of installation and at subsequent annual inspections.
- 4.1.8 The deluge system piping must be located downstream of the water supply valve. All piping upstream of the water supply valve must meet the requirements for fire main and water spray systems as specified in IMO Resolution A.753(18), Appendix 4.
- 4.9 The wet/dry fire endurance testing shall consist of conducting the Level 3 fire endurance testing specified in Appendix 2 of IMO Resolution A,753(18) with the following modifications to the test conditions:
- **4.9.1** For the first 5 minutes of the test, the piping shall be maintained in the dry condition at atmospheric pressure in lieu of containing stagnant water.
- **4.9.2** After completion of the first 5 minutes of the test, the pipe specimen shall be completely filled with flowing water.
- 4.9.3 Air shall be bled from the opposite end of the piping via a test connection until a steady flow of water at the specified flow rate and pressure is observed. The flow rate should not exceed the minimum pressure and flow rate that will be observed at the hydraulically most remote nozzle of the specific deluge system installation. The period from the time of first introducing water to the test specimen until the specified flow rate

and pressure is obtained, shall not exceed one minute. Testing at the specified flow rate and pressure will qualify the piping for all flow rates greater than that specified in the test.

- 4.9.4 The total test time including dry and wet time shall be 30 minutes.
- 4.9.5 All other requirements of Level 3 testing shall be followed without deviation. Alternative acceptance criteria as described in Enclosure (1) of this PFM, may be utilized in lieu of the Acceptance Criteria specified in Appendix 2 of IMO Resolution A.753(18).

APPENDIX: ACCEPTABLE ALTERNATIVE WET/DRY FIRE ENDURANCE TEST METHOD

Wet/Dry Jet-Fire Endurance Testing*

1 Test Method

The test method shall be as set forth by the U.K. Health & Safety Executive, Offshore Technology Report, OTI 95 634, Jet-Fire Resistance of Passive Fire Protection Materials, Sections 7, 8, 9, & 10, with the modifications and additions discussed herein. Where sections of OTI 95 634 refer to specific test specimens, the requirements for tubular sections shall be used.

The piping section, joints or fittings shall be centered in the box so as to be exposed to conditions of direct impingement from the jet flame.

2 Test Specimen

Each pipe should have a length of approximately 3 meters. The test pipe should be prepared with the permanent joint and/or fitting showing the most vulnerability (highest leakage rate) when tested to the Level 3 fire endurance test per IMO Resolution A.753(18). Additional test specimens may be tested, however, they will not be required provided that the piping system has been tested to the IMO Level 3 fire endurance requirements.

If the insulation contains, or is liable to absorb moisture, the specimen should not be tested until the insulation has reached an air-dry condition. This condition is defined as equilibrium with an ambient atmosphere of 50 % relative humidity at 20 ± 5 °C.

The outside diameter of piping shall not exceed 0.35 meters.

3 Test Conditions

The test conditions shall be as set forth in sections 4.9.1, 4.9.2, and 4.9.3 of these guidelines. The duration of the test shall be 20 minutes.

^{*} This test method is currently being refined by the Fire Endurance Section of ASTM Designation: F1173 and will be a referenced standard when completed.

4 Acceptance Criteria

The acceptance criteria shall be the same as set forth in Appendix 2 of IMO Resolution A.753(18) except that the maximum leakage rate when hydrostatically tested to the rated pressure, after the jet-fire exposure shall not exceed 10% of the flow rate of water used during the test.



Memorandum

Subject:

To:

POLICY FILE MEMORANDUM ON THE USE OF FIBER REINFORCED PLASTIC (FRP) GRATINGS AND CABLE TRAYS

Date:

JUN 19 1998

PFM 2-98 9078

Reply to

G-MSE-4

C.S. Myskowski 202-267-1444

Distribution

(a) Marine Safety Manual. Volume II, paragraph 5.C.6

Chief, Office of Design and Engineering Standards

- 1. <u>PURPOSE</u>: This Policy File Memorandum provides guidance on the fire test requirements for use of fiber reinforced plastic (FRP) gratings and cable trays and will be incorporated as a change to reference (a).
- 2. <u>APPLICABILITY:</u> This Policy File Memorandum addresses the fire performance of FRP grating and cable trays for use on inspected vessels, including mobile offshore drilling units (MODUs) and floating production platforms. It is not intended to eliminate any other design criteria or requirements pertaining to the material, construction, or performance of the grating in the non-fire condition, nor is it intended to apply retroactively to applications that have previously received approval on a case-by-case basis.
- 3. BACKGROUND: FRP gratings and cable trays are desirable for use in the marine environment because of their light weight, low thermal conductivity, and resistance to corrosion. However, these materials are typically combustible and exhibit mechanical properties different from steel and thus require careful consideration with respect to fire integrity, combustibility, and smoke generation. As a result of the development of this policy, the use of FRP grating can be expanded beyond the current guidance in reference (a) with confidence that the overall level of fire safety will be maintained.
- 4. <u>DISCUSSION</u>: This Policy File Memorandum addresses qualification and testing of FRP grating for structural fire integrity, and updates the requirements for flame spread, smoke, and toxicity testing of FRP gratings and cable trays. Enclosure (1) provides the fire testing requirements necessary for using FRP grating and cable trays in various locations and services.

SUBJ: POLICY FILE MEMORANDUM ON THE USE OF FIBER REINFORCED PLASTIC (FRP) GRATINGS

5. ACTION: Enclosure (1) of this PFM shall be consulted in lieu of paragraph 5.C.6 on pages 5-4 and 5-5 of Volume II of the Marine Safety Manual. This PFM shall remain in effect until enclosure (1) is incorporated as a change to the Marine Safety Manual. Questions arising which pertain to specific issues not addressed in this policy should be referred to the Commandant (G-MSE-4), U.S. Coast Guard Headquarters, 2100 Second St., S.W., Washington, DC 20593-0001.

MARK G. VANHAVERBEKE CAPTAIN, US COAST GUARD

Dist: G-MSE

MSC

G-MSE-4

Encl: (1) Future Change to the Marine Safety Manual, Volume II, paragraph 5.C.6, Fiber Reinforced Plastic (FRP) Gratings

(2) Marine Safety Manual section being replaced by this PFM

5.C.6. Fiber Reinforced Plastic (FRP) Gratings.

a. General.

- (1) FRP gratings are not specifically addressed in the individual vessel regulations. However, the resins typically used in the manufacture of these gratings are combustible and heat sensitive; therefore, FRP gratings use must be limited based on the requirements discussed below.
- (2) These requirements are not intended to eliminate any other design criteria or requirement pertaining to the material, construction, or performance of the FRP gratings in the non-fire condition.

b. FRP Grating Material Systems.

- (1) All fire integrity, flame spread, smoke, and toxicity testing, where required, shall be conducted on each material system.
- (2) Changes in either the type, amount, and/or architecture, of either the reinforcement materials, resin matrix, coatings, or manufacturing processes shall require separate testing in accordance with the procedures below. Manufacturers should provide evidence, such as enrollment in a follow-up program, that the FRP gratings being installed are the same as those which were tested and approved.

c. Testing Laboratories and Approval.

- (1) The testing laboratory conducting the fire testing described below shall:
 - (a) be engaged, as a regular part of its business, in performing inspections and tests that are the same or similar to the tests described below:
 - (b) have or have access to the apparatus, facilities, personnel, and calibrated instruments that are necessary to inspect and test the FRP gratings; and
 - (c) not be owned or controlled by the manufacturer of the FRP gratings.
- (2) Requests for approval shall be submitted to the Commandant (G-MSE-4) 2100 Second St., S.W., Washington DC, 20593-0001 and shall include the following:
 - (a) a test report containing the information required by 46 CFR 159.005-11; and
 - (b) a list of the FRP gratings and grating systems for which approval is requested.

d. Fire Test Requirements.

- (1) Structural Fire Integrity The structural fire integrity matrix in paragraph 5.C.6.f establishes the structural fire integrity characteristics that FRP gratings should possess, based on location and service. Where a specific application satisfies more than one block in the matrix, the highest level of fire integrity shall be required. The test procedures required to qualify FRP gratings to one of three levels are described in paragraph 5.C.6.e. The Marine Safety Center (MSC) and/or the OCMI shall determine the location and service of the FRP gratings keeping in mind the following considerations for each of the three performance levels:
 - (a) Level 1 (L1): FRP gratings meeting the L1 performance criteria are intended to be satisfactory for use in escape routes or access for firefighting, emergency operation or rescue, after having been exposed to a significant hydrocarbon or cellulosic fire incident. In addition they are also acceptable for the services and functions described for levels L2 and L3.
 - (b) Level 2 (L2): FRP gratings meeting the L2 performance criteria are intended to be satisfactory for use in open deck areas where groups of people are likely to assemble such as temporary safe refuge or lifeboat embarkation areas. In addition they are also acceptable for the services and functions described for level L3.
 - (c) Level 3 (L3): FRP gratings meeting the L3 performance criteria are intended to be satisfactory for use in egress routes and any areas that may require access for firefighting, rescue or emergency operations during exposure to or shortly after exposure to a transitory hydrocarbon or cellulosic fire.
- (2) Fire Retardance All FRP gratings should be fire retardant; this can be demonstrated by testing to ASTM E-84, Standard Test Method for the Surface Burning Characteristics of Building Materials with a flame spread rating not to exceed 25 or by meeting the requirements in paragraph 5.C.6.d(3)(a) or (b) below.
- (3) Flame Spread All FRP gratings, except those fitted on open decks and within tanks, cofferdams, void spaces, pipe tunnels and ducts, should have low flame spread characteristics as determined by one of the following test procedures:
 - (a) tested to ASTM E-84 with a flame spread rating not to exceed 20; or

^{*} The structural fire integrity requirements are intended for self-supporting personnel platforms or walkways and are not intended for grating overlayed on steel decking or used in other applications such as pipe guards, seachest screenings, safety guards, etc.

- (b) tested to IMO Resolution A.653(16), Recommendation on Improved Fire Test Procedures for Surface Flammability of Bulkhead, Ceiling and Deck Finish Materials and meeting the criteria for bulkheads, linings, or ceilings.
- (4) Smoke Generation FRP gratings within accommodation, service and control spaces, should have low smoke characteristics as determined by one of the following test procedures:
 - (a) tested to ASTM E-84 with a smoke developed rating not to exceed 10; or
 - (b) tested in accordance with the IMO Fire Test Procedures Code (FTPC), Resolution MSC.61(67), Part 2 Smoke and Toxicity Test, and meeting the criteria established for materials used as bulkheads, linings, or ceilings.

e. Structural Fire Integrity Test Procedures.

- (1) Level 1-To be qualified as level 1 (L1), the FRP gratings shall meet the requirements for qualification as level 3 and level 2, and in addition shall be subjected to the following test procedures:
 - (a) Three (3) FRP grating specimens, after being subjected to the level 2 testing, shall be unloaded and prepared for impact testing in the manner specified for horizontal specimens in ASTM E-695, Standard Method of Measuring Resistance of Wall, Floor, and Roof Construction to Impact Loading. The test specimens shall be secured as required in section 8.3 of ASTM E-695 except that the span shall be 200 mm less than the specimen length. A lead shot bag of 40 kg mass shall be dropped once from a height of 2 m such that the point of impact is in the center of the span. The specimens shall then be uniformly loaded as required by the level 2 test procedures.
 - (b) The test will be considered successful if all three (3) specimens remain intact after being subjected to the impact test and the level 2 loading test. Failure will be indicated by collapse of one or more of the gratings.
- (2) Level 2 To be qualified as level 2 (L2), the FRP gratings shall meet the requirements for qualification as level 3, and in addition shall be subjected to the following test procedures:
 - (a) On the FRP grating specimen and the steel grating specimen subjected to the level 3 post-loaded testing, the specimen shall be gradually loaded in increments not to exceed 20 kg, placed in such a manner as to represent a uniformly distributed load across the span.

- (b) The test will be considered successful if the FRP grating remains intact at a load greater than or equal to a uniform 4.5kN/m² (94 lbf/ft²) or greater than or equal to the steel grating failure loading, whichever is less. Failure will be indicated by collapse of the grate.
- (3) Level 3 To be qualified as level 3 (L3), the FRP gratings should be subjected to the following fire test procedures for both the post-loaded and pre-loaded tests and conditions:
 - (a) A fire test will be conducted in accordance with ASTM E-119, Standard Test Method for Tests of Building Construction and Materials. Two tests shall be conducted in the ASTM E-119 furnace for each FRP grating design. The first fire test shall be conducted with the specimens under the specified load (pre-loaded) and the second fire test will be conducted on unloaded specimens (post-loaded). The time-temperature curve shall be the standard for E-119 or the ISO equivalent. The duration of the tests shall be as specified below.
 - (b) Each test specimen shall be 300-350 mm wide to allow for the differences in the spacing of longitudinal supporting members. The length of each test specimen shall be the length of the maximum span to be seen in service plus 200 mm. Four test specimens shall be prepared as described above; two of the proposed FRP gratings and two of a similar steel gratings that would be used in the same location constructed to the applicable regulations and standards (steel gratings rated at a minimum of 4.5 kN/m² (94 lbf/ft²) uniform loading with a 1.67 factor of safety are acceptable).
- (c) The pre-loaded test shall consist of the following:
 - (i) one steel grating specimen and one FRP grating specimen shall be placed adjacent to one another in the furnace simply supported on two I-beams with a minimum flange width of 100 mm at an elevation of at least one half of the furnace height or a minimum of 300 mm above the burners;
 - (ii) the specimens shall be placed on the I-beams such that 100 mm of each side of the specimen rests on each of the two I-beams;
 - (iii) a static load represented by a 40 kg mass shall be placed in the center span of the test specimens;
 - (iv) the 40 kg mass load shall consist of a steel container filled with sand, the base of which shall be square with an area of 0.9 m²;
 - (v) arrangements shall be made to measure the deflection at the center of the span of each of the loaded specimens during the test with a degree of

accuracy of ±5 mm.

- (vi) the two specimens shall be subjected to the time-temperature curve specified in the ASTM E-119;
- (vii) deflection of the two loaded test specimens shall be measured throughout the duration of the fire test and the average furnace temperature shall be recorded when each of the two specimens has deflected a distance of L/10 (failure point) from the horizontal where L is equal to the maximum unsupported span of the specimens; and
- (viii) the test will be considered successful if the difference between the average furnace temperature at the time of failure of the steel grating and the average furnace temperature at the time of failure of the FRP grating is less than 100 °C (180 °F).
- (e) The post-loaded test shall consist of the following:
 - (i) one steel grating specimen and one FRP grating specimen shall be placed adjacent to one another in the furnace simply supported on two I-beams with a minimum flange width of 100 mm at an elevation of at least one half of the furnace height;
 - (ii) the specimens shall be placed on the I-beams such that 100 mm of each side of the specimen rests on each of the two I-beams;
 - (iii) the two specimens shall be subjected to the time-temperature curve specified in the ASTM E-119 for a duration of 60 minutes;
 - (iv) at the end of the 60 minutes the specimens will be allowed to cool and shall then be subjected to a static load represented by the 40 kg mass specified in the pre-loaded test above, placed in the center span of the test specimens; and
 - (v) the test will be considered successful if the FRP grating specimen is intact at the end of the test and does not collapse under the 40 kg mass load.

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f. Structural Fire Integrity Matrix.

Location	Service	Fire
Machinery Spaces	access for firefighting, emergency operation or rescue	Integrity L1
C	Personnel walkways, catwalks, ladders, platforms or access areas other than those described above	L3
Cargo Pump Rooms	All personnel walkways, catwalks, ladders, platforms or access areas	LI
Cargo Holds	Walkways or areas which may be used for escape, or access for firefighting, emergency operation or rescue	L1
	Personnel walkways, catwalks, ladders, platforms or access areas other than those described above	None required
Cargo Tanks	All personnel walkways, catwalks, ladders, platforms or access areas	None
Fuel Oil Tanks	All personnel walkways, catwalks, ladders, platforms or access areas	None
Ballast Water Tanks	All personnel walkways, catwalks, ladders, platforms or access areas	required ² None
Cofferdams, void spaces, double bottoms, pipe tunnels, etc.	All personnel walkways, catwalks, ladders, platforms or access areas	required ³ None required ³
Accommodation, service, and control spaces	All personnel walkways, catwalks, ladders, platforms or access areas	L1
Lifeboat embarkation or temporary safe refuge stations in open deck areas	All personnel walkways, catwalks, ladders, platforms or access areas	L2
Open Decks or semi-enclosed	Walkways or areas which may be used for escape, or access for firefighting, emergency operation or rescue	L3*
If the machinery space of	Personnel walkways, catwalks, ladders, platforms or access areas other than those described above oes not contain any internal combustion machinery, other oil burning.	None required

If the machinery space does not contain any internal combustion machinery, other oil burning, oil heating, or oil pumping units, fuel oil filling stations, or other potential hydrocarbon fire sources and has not more than 2.5 kg/m² of combustible storage, gratings of L3 integrity may be used in lieu of L1.

²If these spaces are normally entered when underway, gratings of L1 integrity shall be required.

³If these spaces are normally entered when underway, gratings of L3 integrity shall be required.

Vessels fitted with deck foam firefighting systems require gratings of L1 integrity for foam system operational areas and access routes.

g. Other Authorized Uses.

- (1) The OCMI may authorize the use of FRP gratings without Commandant approval in applications where structural fire integrity of the FRP gratings is not a concern, provided they meet the applicable fire retardance, flame spread and smoke generation requirements as set forth in paragraphs 5.C.6.d(2), (3), & (4). Applications where the use of FRP gratings have been authorized in the past, without any structural fire integrity requirements, include the following:
 - (a) sea chest coverings;
 - (b) small sundæk awnings and supports;
 - (c) lifeboat bilge flooring;
 - (d) electrical control flooring;
 - (e) pipe guards on deck, in cargo holds, and in enginerooms;
 - (f) removable guards over hawseholes, anchor hawsepipes, and scuppers;
 - (g) personnel barriers, such as protection for electrical panels; and
 - (h) ship staging and work platforms (Occupational Safety and Health Administration (OSHA) requirements may also apply).

5.C.7 Fiber Reinforced Plastic (FRP) Cable Trays.

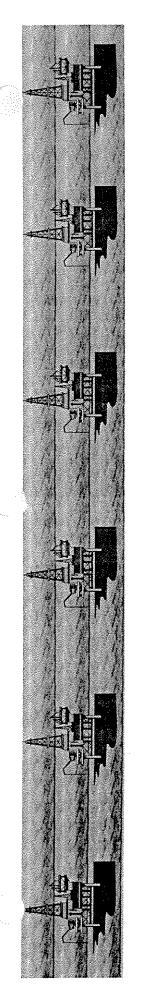
- a. General. Cables should be supported by metal hangars as required by section 20.5 of IEEE Standard 45, Recommended Practice for Electric Installations on Shipboard. FRP cable trays may be used anywhere provided:
 - (1) they are fire-retardant as described in section 5.C.6.d(2) above;
 - (2) they comply with the applicable flame spread requirements for FRP gratings specified in paragraph 5.C.6.d(3) above;
 - (3) they comply with the applicable smoke generation requirements for FRP gratings specified in paragraph 5.C.6.d(4) above; and
 - (4) their failure, will not cause the cables they are supporting to fall and hinder escape or access by firefighters.

- 5.C.4. b. (cont'd) The use of lap-welded seams in tank barges should be discouraged, but not prohibited unless the inspector finds a failure to meet these requirements.
 - 5. Single-Dogged Hatches And Scuttles. Hatches on inspected vessels are generally subject to the approval of the CMI, according to their suitability for the intended locations on board and their use. There is no provision for type approval and they are not normally seen in detail on plans submitted for the OCHI's approval.

6. Fiberglass Gratings.

- General. Fiberglass gratings are not specifically addressed in the individual vessel regulations. However, fiberglass is combustible; therefore, its use must be limited based on the general requirements to reduce hazards from fire. Basically, fire-retardant fiberglass may be used anywhere except in accommodation areas, and in any other area where their failure could hinder escape or access by firefighters. Although all fiberglass must be fire-retardant, there are no Coast Guard approvals for fire-retardant fiberglass gratings or cable trays. Rowever, the OCMI may authorize its use in particular installations, considering the fire retardance and the criteria in subparagraph 5.C.6.c below. The manufacturer should provide the Coast Guard inspector with appropriate test data; a report showing a flame spread rating less than 25 according to the American Society for Testing Materials (ASTM) Standard E-84 would constitute appropriate evidence. Fiberglass cable trays may be used in exterior locations and in machinery spaces, provided that they are not installed in concealed spaces.
- b. Restrictions On Use. Fiberglass gratings may not be used within the accommodation area nor in areas where their failure could hinder escape or firefighter access. Vessels fitted with deck foam firefighting systems must have steel or equivalent access to the foam monitors.
- c. Authorized Uses. Since the approval of fiberglass cable trays and gratings is so dependent on the specific location and application, it is not possible for the Commandant to grant general approvals. In the past, however, the use of fiberglass gratings aboard inspected vessels has been authorized in the following areas:
 - (1) Sea chest screenings;
 - (2) Small sundeck awnings and supports;
 - (3) Lifeboat bilge flooring;
 - (4) Electrical control flooring;
 - (5) Pipe guards on deck, in cargo holds, and in enginerooms;

- 5.C.6.c. (6) Fore and aft main deck catwalks;
 - (7) Main deck crossover catwalks;
 - (8) Removable guards over hawseholes, anchor hawsepipes, and scuppers;
 - (9) Personnel barriers, such as protection for electrical panels;
 - (10) Ladders, platforms, and catwalks located within double bottoms, bilges, peak tanks, fuel tanks, liquid bulk cargo tanks, and other spaces not normally entered when underway;
 - (11) Ship staging and work platforms (Occupational Safety and Health Administration (OSHA) requirements may also apply);
 - (12) Platforms and ladders located on radar, radio, or other electrical apparatus masts;
 - (13) Platforms or walkways on kingposts;
 - (14) Overlay on existing weather decks to provide slip resistant, self-draining walking surfaces;
 - (15) Overlay on steel decking around electrical equipment to provide for insulation and safety of personnel; and
 - (16) Elevated flooring in boatswain's lockers.
- D. Tank Vessel Repairs, Alterations, And "Hot Work." The problem of avoiding casualties on tank vessels under repair is extremely complicated, due to the possible presence of explosive gases and sources of ignition created by the use of flame or spark producing tools. No repairs or alterations involving the safety of a tank vessel may be made until the requirements of 46 CFR 35.01-1 have been met. These regulations set forth the provisions under which a certified marine chemist will make a decision as to whether the work can be accomplished safely (see section 5.1 below). A tank vessel may have "hot work" performed in or on the boundaries of a tank previously containing flammable liquids only after the tank has been cleaned and gas-freed by conventional methods, and when the surrounding tanks have been cleaned and gas-freed or inerted with carbon dioxide or water. 33 CFR 126.15(c) applies to vessels conducting hot work while moored at designated waterfront facilities.
- E. Inspection And Repair Of Tank Barges.
 - 1. Introduction. Tank barges employed primarily in river or inland service are generally towed alongside or pushed shead, as opposed to being towed astern. Barges in these services are subjected to rigors of locking and fleeting operations that are not normally experienced by seagoing barges or self-propelled vessels. As a result, some distinct structural problems have evolved.



SHORT COURSE

Selection, Design and Maintenance of Fiberglass Pipe Systems for Offshore Applications

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